Environmental Security Technology Certification Program

(ESTCP)

In-situ Substrate Addition to Create Reactive Zones for Treatment of Chlorinated Aliphatic Hydrocarbons: Hanscom Air Force Base

Contract #41624-99-C-8032

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In-situ Substrate Addition to Create Reactive Zones for Treatment of Chlorinated Aliphatic Hydrocarbons: Hanscom Air Force Base

Prepared for:
Air Force Center for Environmental Excellence (AFCEE)
3207 Sydney Brooks
Brooks AFB, Texas 78235-5344
POC: Mr. Jerry Hansen

and

Environmental Security Technology Certification Program (ESTCP)
901 North Stuart Street, Suite 303
Arlington, Virginia 22203
POC: Dr. Andrea Leeson

Prepared by:
ARCADIS G&M, Inc.
4915 Prospectus Dr., Suite F
Durham, North Carolina 27713
Christopher C. Lutes, Victor D'Amato P.E., Angela Frizzell P.G.,
Michael Hansen P.E., Glen Gordon P.E., Peter Palmer P.E., P.G.
and Suthan Suthersan Ph.D., P.E.

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1,2-DCE	1,2-Dichloroethene
1,2-DCA	1,2-Dichloroethane
1,1,1-DCA	1,1,1-Dichloroethane
1,1,1-TCA	1,1,1-Trichloroethane
AFB	Air Force Base
AFCEE	Air Force Center for Environmental Excellence
bgs	below ground surface
BOD	Biochemical Oxygen Demand
BRAC	Base Realignment and Closure
CAH	Chlorinated Aliphatic Hydrocarbons
CERCLA	Comprehensive Environmental Response Compensation and Liability Act
CF	Chloroform
cis-1,2-DCE	*cis*-1,2-Dichloroethene
COC	Constituents of Concern
COD	Chemical Oxygen Demand
COTS	Commercially Off-The-Shelf
CT	Carbon Tetrachloride
DCE	Dichloroethene
DNAPL	Dense, Non-Aqueous Phase Liquid
DO	Dissolved Oxygen
DOC	Dissolved Organic Carbon
DoD	Department of Defense
EARP	Enhanced Anaerobic Reductive Precipitation
ERD	Enhanced Reductive Dechlorination
ESTCP	Environmental Security Technology Certification Program
GC	Gas Chromatograph
H_2	Hydrogen
IRZ	In-situ Reactive Zone
K	Hydraulic Conductivity
L	Liters
MADEP	Massachusetts Department of Environmental Protection

MC	Methylene Chloride
MCL	Maximum Contaminant Level
mg/L	milligrams per Liter
MNA	Monitored Natural Attenuation
NAS	National Academy of Science
ORP	Oxidation Reduction Potential
PBC	Performance Based Contract
PCE	Tetrachloroethene
PCP	Pentachlorophenol
psig	per square inch gauge pressure
PVC	Polyvinyl Chloride
RCRA	Resource Conservation and Recovery Act
STL	Severn Trent Laboratories
TBP	Tributyl Phosphate
TCA	Trichloroethane
TCE	Trichloroethene
TDS	Total Dissolved Solids
TOC	Total Organic Carbon
TPH	Total Petroleum Hydrocarbon
trans-DCE	*trans*-1,2-Dichloroethene
TVOC	Total Volatile Organic Compound
µg/L	micrograms per liter
UIC	Underground Injection Control
U.S. EPA	United States Environmental Protection Agency
VC	Vinyl chloride
VER	Vacuum-Enhanced Recovery
VOC	Volatile Organic Compound

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ACKNOWLEDGEMENTS

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PREFACE

ARCADIS is the owner of Contractor Patented Technology for the in-situ addition of carbohydrate substrate material to create reactive zones for the removal of chlorinated hydrocarbons from groundwater as set forth in U.S. Patent Nos. 6,143,177 and 6,322,700.

To discuss application of this technology at government sites please contact:

- Van Sands at ARCADIS in Denver CO 720-344-3792 regarding legal and contractual matters and
- Chris Lutes of ARCADIS in Durham, NC at 919-544-4535 or clutes@arcadis-us.com regarding technical information, or
- Jerry Hansen at AFCEE 210-536-4353 or jerry.hansen@brooks.af.mil.

For commercial application please contact ARCADIS only, at the above listed phone numbers.

EXECUTIVE SUMMARY

The general purpose of this demonstration program was to evaluate the efficacy of the In-Situ Reactive Zone (IRZ)/Enhanced Reductive Dechlorination (ERD) technology to remove chlorinated aliphatic compounds (CAHs) from impacted groundwater in a range of geologic conditions and CAH concentrations. The demonstration also helped determine the rates of mass removal of CAHs in groundwater at the demonstration site at Hanscom Air Force Base.

Ultimately, the objectives of the demonstration were to demonstrate the ability to remediate contaminants in the subsurface over a relatively short time period (from one to five years in typical full-scale applications) and to gather information that can be used to estimate long term treatment effectiveness, life span and costs. The results of the demonstration were used to develop a protocol for the use of ERD technology for CAHs at DoD facilities (Suthersan, 2002). Also important in this demonstration was to show that the degradation of CAHs does not "dead-end" at undesirable by-products such as cis-1,2-dichloroethene (cis-1,2-DCE) and/or vinyl chloride (VC). The primary benefits of ERD technology include ease of regulatory acceptance, in-situ nature and relatively low cost. Potential limitations to the application of the IRZ technology using soluble carbohydrates can include the following:

- Intermediate degradation products such as VC can be formed; however, proper system design can ensure their further degradation.
- Production of reduced gases or secondary water quality impacts from byproduct organic compounds, fermentation byproducts or mobilized metals is possible. The effects of these constituents usually do not extend beyond the reactive zone, but they should be monitored and addressed during implementation. At the demonstration site, secondary water quality impacts (including metals mobilization and high COD/BOD) were observed, but as expected were limited to the area of the reactive zone and did not appear to be significant downgradient. Ketones were generated as metabolic byproducts of molasses biodegradation, but did not appear to pose an appreciable risk.
- ERD's effectiveness on large pools of free-phase dense, non-aqueous phase liquid (DNAPL) has not been proven although it does appear to be applicable to sorbed or residual DNAPL.

Scope and Location of Demonstration

The demonstration area at Hanscom is downgradient of an area that has been used in the past for research and training exercises, including the dumping of drummed pyrokinetic waste for burning. Residual CAHs remain beneath this area of the site in sorbed and dissolved phases and evidence also suggests the presence of emulsified or pooled DNAPL. The semi-confined lower sandy till aquifer (the target zone for the demonstration) rests directly on bedrock at a depth of about 50 feet. Before treatment, trichloroethene (TCE) concentrations in the lower aquifer at the RAP1-6 well cluster averaged between 1,000 and 2,000 µg/L with elevated levels of both cis-1,2-DCE (2,000 to 5,000 µg/L) and VC (500 to 1,300 µg/L). The site was moderately reducing (DO <1.5 mg/l, ORP typically 0 to -50 mV) with pH ranging from 6.0 to 6.5 prior to treatment.

The active treatment phase of the demonstration was from October 2000 to October 2002. A total of forty-seven injections were conducted in a single injection well. Over this time, a total of 1,250 gallons of raw blackstrap molasses, 11,250 gallons of dilution water, 7,575 gallons of push water and 4,732 grams of potassium bromide were injected. Monitoring was conducted during the demonstration to gauge technology effectiveness, describe changes in biogeochemical conditions and gather process monitoring feedback.

Summary of CAH Treatment Results

Our discussion of CAH treatment focuses primarily on the two monitoring wells that received substantial doses of substrate TOC - RAP 1-6T and IRZ-1 - and secondarily on the injection well. The two monitoring wells were also the only wells screened in the target zone in which substantially increased levels of methane were observed.

The best treatment results were observed at IRZ-1 (approximately 45 feet downgradient from the injection well). At this well, highly effective treatment of TCE was observed five months after injections began and shortly after single injections with water pushes began (>95% reduction vs. pretest concentration). Substantial treatment of cis-1,2-DCE (eventually >85% reduction in pretest concentration) was not observed until a year later, during a second period of high TOC delivery. By that time, complete degradation was evidenced by the substantial increase in ethene production. The rate of ethene production continued to climb through the end of the demonstration in October 2002, indicating that treatment effectiveness continued to increase after two years of system operation. Ethene concentrations at this well increased to more than 20 times the pre-test value.

At RAP1-6T, a sharp decline in TCE was observed within six months of the first injection, coinciding with or slightly preceding the appearance of substrate. TCE levels for seven straight monitoring rounds were at 10% or less of the average of the preceding 10 years. This result exceeded the 80%-in-one-year treatment objective. Then, due to changes in the groundwater flow direction, the IRZ shifted away from RAP1-6T and IRZ-1. As a result of the shift, TCE, cis-1,2-DCE and VC concentrations rebounded at RAP1-6T. These concentrations dipped again when substrate levels increased, although it appears that the typical groundwater flow direction was somewhat more easterly rather than southeasterly as planned. Thus, this well was probably at the fringe of the effective reactive zone for much of the demonstration period.

Although the injection well is by definition a less accurate indicator of the overall effectiveness of the reactive zone than downgradient wells, it is useful to note that substantial evidence of effective treatment of all chlorinated species was seen at the injection well, even in data corrected for the dilution effect of the injected solution. Concentrations of TCE were reduced by more than 95% and VC by 85% over a long period from May 2001 through October 2002. DCE decreased substantially less during this period (at most about 75%). This suggests that although CAHs were being completely degraded, desorption from a localized source area upgradient from the injection well continued.

The wells that did not get substantial, consistent doses of substrate showed no evidence of treatment or at most only modest decreases in TCE (IRZ-2, IRZ-3, IRZ-4 and IRZ-5 in the targeted lower aquifer, RAP1-6R in the bedrock aquifer and RAP1-6S in the upper aquifer). This strengthens the conclusions that substrate availability is linked with improved biodegradation and that contaminant removal was attributable to enhanced biodegradation rather than displacement.

Analysis of CAH Data: Conditions Required for Enhanced Biodegradation

Data for IRZ-1 and RAP1-6T demonstrate that TCE concentrations decrease when substrate concentration increases. However, this correlation between TCE degradation and substrate availability clearly does not hold for DCE degradation. This suggests that substrate is a necessary but not sufficient condition for complete enhanced biodegradation. Data suggests that it took almost a year of regular substrate injections and system adjustments to overcome the oxidative poise of more preferential electron acceptors and reach methanogenic conditions at or upgradient of IRZ-1. This result is also in keeping with our theoretical understanding that enhanced biodegradation, especially the biodegradation of cis-1,2-DCE, is more favored under methanogenic conditions than sulfate-reducing conditions (Suthersan 2002).

Taken together, this data set is consistent with a theoretical understanding in which both consistent substrate dosing and methanogenic conditions are required for optimal treatment (Suthersan, 2002). Therefore, the addition of sufficient carbohydrate substrate to drive redox values into the methanogenic or sulfate-reducing range in bacterial zones distant from the line of injection wells is required to achieve rapid, complete biodegradation.

Comparison of Results with Primary Objectives

During the two-year demonstration project, highly effective, complete TCE removal was observed in a source area that had a long history of fairly stable TCE concentrations before treatment. Evidence of complete treatment – a buildup of ethene, reduction in cis-1,2-DCE and no accumulation of vinyl chloride - was seen in the most effectively treated downgradient wells. TCE reductions in these wells (RAP1-6T, IRZ-1) exceeded the 80%-in-one-year treatment objective. Effective treatment was seen only where substantial substrate (molasses and its breakdown products) was observed in downgradient monitoring wells. The layout of the injection and monitoring well system was designed for a consistent southeasterly groundwater flow; however, during the demonstration period, the direction of flow varied, often to the east. Thus, it is suspected that a larger IRZ was formed than what was observed, but that the monitoring well network was not positioned to completely detect it.

The data from RAP1-6T, IRZ-1 and the injection well do not show evidence of "accumulation" or "dead-ending" at DCE or vinyl chloride. On the contrary, the data discussed above and especially the increases in ethene show that complete degradation was achieved in these wells. Therefore, the primary performance objectives were met for the wells within the reactive zone.

Cost Analysis

Cost comparisons provided in the report are based on a plume-wide application to a dissolved plume with residual, sorbed material in a source area. Applied under appropriate conditions, ERD provides significant cost savings over conventional pump and treat technology, and compares favorably with other more innovative technologies in a comparison including ex-situ substrate-enhanced bioremediation with recirculation, a zero valent iron barrier and natural attenuation. Estimated unit costs will be provided at the conclusion of the project in the cost and performance report when complete financial information is available.

1. Introduction

1.1 Background

Chlorinated solvent contamination of groundwater is a widespread problem at many military and civilian facilities. This class of compounds includes widely used industrial chlorinated aliphatic hydrocarbons (CAHs) such as carbon tetrachloride (CT), methylene chloride (MC), trichloroethane (TCA), trichloroethene (TCE) and tetrachloroethene (PCE). In addition to their roles in many industrial processes, CAHs have historically been used for cleaning and degreasing such diverse products as aircraft engines, automobile parts, electronic components and clothing. Contamination of groundwater by mobile metals (e.g., hexavalent chromium, lead, arsenic, nickel, mercury and cadmium) is also widespread at military facilities due to the use of these metals in ordnance, armament, armor, and as components of corrosion prevention coatings on vehicles. Because of the integral nature of CAHs and metals in efficient military operations, it is not surprising that the Unites States Armed Forces (USAF) are often faced with widespread, costly remediation problems related to these compounds.

The conventional remedy for CAH contamination in groundwater is groundwater extraction and ex-situ treatment, typically with air stripping or carbon adsorption, also known as pump and treat or in-situ air sparging. An alternative to these conventional technologies that has already been used at over 130 commercial sites is In-situ Reactive Zone (IRZ) technology for the remediation of CAHs and metals. The IRZ demonstration involves the addition of a food grade carbohydrate substrate, which serves as a supplemental energy source for microbiological processes in the subsurface. This substrate is typically molasses although these substrates can include high fructose corn syrup, whey, etc. (Suthersan, 2002). Through this subsurface molasses injection, the existing aerobic or mildly anoxic aquifers can be altered to highly anaerobic reactive zones. This creates suitable conditions for the biodegradation of CAHs and/or the precipitation of selected metals in insoluble forms. Thus this technology can be more specifically referred to as Enhanced Reductive Dechlorination (ERD) or Enhanced Anaerobic Reductive Precipitation (EARP). Other available innovative remedies for CAH contamination in groundwater include chemical oxidation, phytoremediation and vacuum enhanced recovery.

The primary benefits of this technology include ease of regulatory acceptance, in-situ nature and relatively low cost. The benefits of ERD technology include its record of successful application under the following conditions:

- *At Various Constituent Concentrations* –Areas containing dissolved CAH concentrations in excess of 160 milligrams per liter (mg/L) have been successfully treated. Much more dilute plumes with concentrations of target constituents in the 10 – 100 micrograms per liter (µg/L) range have also been treated successfully.
- *In Varied Geologies* –The ERD technology has been applied at sites with widely differing geologic and hydrogeologic settings, from low permeability silts and clays, to high permeability alluvial deposits, to bedrock settings and with groundwater velocities ranging

from a few feet per year to several feet per day. However, as discussed in Section 2, there are permeability and velocity limits beyond which the technology cannot be implied.

- *Under Multiple Regulatory Programs* – The ERD technology has been applied under multiple regulatory programs, including Comprehensive Environmental Response Compensation and Liability Act (CERCLA) and Resource Conservation and Recovery Act (RCRA), and under the jurisdiction of politically sensitive regulatory agencies such as the California Regional Water Quality Control Board. It has also been applied in several countries outside the U.S.

1.2 Objectives of the Demonstration

1.2.1 Objectives

The general purpose of this demonstration program was to evaluate the efficacy of the ERD technology to remove CAHs from the impacted groundwater in a range of geologic conditions and CAH concentrations. Ultimately, the objectives of the demonstration were to demonstrate the ability to remediate contaminants in the subsurface over a relatively short time period (from one to five years in typical full-scale applications) and also to gather information that can be used to estimate long term treatment effectiveness, life span and costs. The primary goal of this technology demonstration is to use the results to develop a protocol for use of ERD technology for CAHs at Department of Defense (DoD) facilities (this document, soon to be finalized, is formally titled “Technical Protocol for Using Soluble Carbohydrates to Enhance Reductive Dechlorination of Chlorinated Aliphatic Hydrocarbons” [Suthersan, 2000]). Performance objectives are discussed in more detail in Section 3.1. The demonstration helped determine the rates of mass removal of CAHs present in the groundwater at the demonstration sites.
Also important in the demonstration was to show that the degradation of CAHs does not “dead-end” at undesirable by-products such as *cis*-1,2-dichloroethene (*cis*-1,2-DCE) and/or vinyl chloride (VC).

To meet these objectives, a pilot test of the technology was conducted at Hanscom Air Force Base (AFB). Hanscom AFB is located in Middlesex County, Massachusetts, approximately 14 miles northwest of downtown Boston. The area selected for the demonstration at Hanscom is downgradient from Site 1, a former fire training area. Site 1 is located on Hartwell’s Hill, northwest of the overrun for Runway 23 and southeast of Hartwell Road, as shown in Figure 1-1. A CAH plume in this area has exhibited TCE concentrations between 1,000-2,000 µg/L, *cis*-1,2-DCE concentrations of 2,000-5,000 µg/L, and VC concentrations of 500-1,300 µg/L. Other physical characteristics of the subsurface at this site are listed in Table 1-1. The pilot test was conducted using molasses as a carbohydrate source, over a period of two years. Extensive monitoring data were collected before and during the test to address performance criteria. Three full monitoring events and five abbreviated monitoring events were conducted.

1.3 Regulatory Drivers

Groundwater impacts by CAHs at DoD sites are regulated under the RCRA and CERCLA programs. Hanscom AFB is a CERCLA (superfund) site, regulated by the EPA.

The overall remedial goals for this particular site are to achieve cleanup goals consistent with current and foreseeable future uses. For groundwater, the long-term cleanup goal is to achieve drinking water standards, since this site lies within an area classified as GW-1 (a potential drinking water supply) by the Massachusetts Department of Environmental Protection (MADEP). For the CAHs detected at this Site, the MADEP's GW-1 standards are equivalent to the United States Environmental Protection Agency (U.S. EPA) Maximum Contaminant Levels (MCLs).

Under an Interim Record of Decision, a groundwater pump and treat system is operating in the demonstration area. Operation of the pump and treat system since 1991 has succeeded in substantially reducing TCE concentrations, but TCE is still well above the MCL and may have reached an asymptote. For this demonstration project, the objective was to determine if the natural attenuation processes could be enhanced to accelerate the progress towards the site-wide remedial goal.

The demonstration was successful in achieving the MCL for TCE. MCLs for TCE daughter products were not attained due to variable groundwater flow directions and thus inconsistent dispersal of reagent. However, generation of ethene was observed, indicating that TCE was being completely degraded without "dead-ending" at intermediate compounds, suggesting that remediation of TCE daughter products to MCLs could also be achieved using ERD technology.

1.4 Stakeholder/End-User Issues

Stakeholders and end-users of ERD technology are concerned foremost with the issue of CAH cleanup. Under appropriate conditions, ERD offers significant advantages over conventional pump and treat technology, including lower cost and reduced treatment time. The advantages and limitations of the technology are discussed in detail in Section 2.4. The production of intermediate products is a potential concern to stakeholders and regulatory agencies. The ERD process converts more highly chlorinated CAHs to less chlorinated and eventually non-chlorinated end products. The cascading reactions can result in the production of VC. This product is more carcinogenic than the parent compound. Reductive dechlorination of VC should also occur with the ERD process, and it is also quickly biodegraded by aerobic microorganisms. For these reasons, the production of VC or other intermediate products is considered a temporary situation and does not represent a major impediment to the technology but should be monitored during application of the technology.

Another stakeholder/regulatory issue can be the production of gases such as methane, hydrogen sulfide, and carbon dioxide, and the migration and potential accumulation of these gases in the vadose zone. Concentrations of these gases can accumulate in the subsurface, when structures in the vicinity do not allow for passive diffusion of these gases. For this reason, vapor-phase concentrations of these compounds are monitored when a potential concern exists to ensure that safe conditions are maintained. If required, venting of subsurface gases or a modified donor injection routine will be used to protect against exposure or accumulation. This issue is not considered to be a major impediment to technology implementation, but must be considered.

Secondary water quality impacts from ERD can occur due to the by-products of substrate consumption as measured by parameters such as chemical oxygen demand (COD), biochemical oxygen demand (BOD), total dissolved solids (TDS), taste, odor, and sulfides. However these impacts are typically limited to the reactive zone itself. These byproducts, which are typical of many natural processes in which bacteria consume a food source, are generally rapidly consumed when the conditions become more aerobic on the edges of the reactive zone. Secondary water quality impacts can also occur from mobilization of metals naturally occurring in the solid phase into the groundwater. Although enhanced anaerobic in-situ bioremediation processes will, in general, reduce the mobility of many metals (indeed it has been successfully used for the treatment of many), it will solubilize some other naturally occurring metals in the reactive zone (e.g., iron, manganese, and arsenic). However, even in solubilized form under anaerobic conditions, metals such as arsenic are substantially retarded by adsorption to the aquifer matrix. Furthermore, it is generally believed that they will be reprecipitated/immobilized downgradient of the reactive zone when the conditions return to their preexisting state (which, for the purposes of this discussion, is assumed to be aerobic). Similarly, reprecipitation/immobilization will occur within the IRZ area some time after system shutdown. These reducing conditions are by no means unique to IRZ systems – they occur, for example, at sites of total petroleum hydrocarbon (TPH) releases and landfills as well.

Molasses itself has been mentioned as a potential source of metals. Available analyses of metals in typical molasses-water mixtures used in IRZ applications have shown concentrations below regulatory standards. Injected metals did not produce secondary water quality issues in this demonstration (see Section 4.3.5). However, this is a potential issue that should be considered in the design phase for IRZ projects. The paucity of available data suggests that further work should be done to explore the metallic content of different sources of molasses.

Thus the potential for secondary water quality impacts needs to be fully identified and addressed during design and in consultation with all applicable regulatory agencies and the public.

As discussed in Section 4.3.5, secondary water quality impacts (including metals mobilization and high COD/BOD) were observed but as expected were limited to the area of the reactive zone and did not appear to be significant downgradient. Although ketones were generated as metabolic byproducts of molasses biodegradation they did not appear to pose an appreciable risk. Gas production was not an issue at this site since the demonstration was conducted in an open area, far from buildings or other structures where gases could accumulate.

2. Technology Description

2.1 Technology Development and Application

2.1.1 General Technology Description and History

ERD technology is intended to facilitate and expedite the biological reductive dechlorination of CAHs through the well-documented mechanisms pictured in Figure 2-1. The ERD technology stimulates indigenous microbiological organisms through the engineered addition of electron donors, which contain degradable organic carbon sources.

The general mechanism behind the application of ERD technology relies on enhancing or inducing the bioremediation of CAHs through periodic subsurface injection of a soluble electron donor solution (typically comprised of a carbohydrate such as molasses, whey, high fructose corn syrup, lactate, butyrate, or benzoate). Through periodic subsurface substrate injection, the ERD technology alters existing aerobic or mildly anoxic aquifers to anaerobic, microbiologically diverse, reactive treatment zones. Within such zones, conditions are conducive for the bioremediation of CAHs.

ERD technology facilitates and expedites the degradation of CAHs through biological reductive dechlorination. Chlorinated compound reduction can be a biologically mediated reaction that entails transferring electrons to the substrate of interest from various initial electron donors. The more oxidized the chlorinated compound is, the more susceptible it is to reduction.

Reductive dechlorination occurs when aquifer bacteria utilize chlorinated solvent molecules as electron acceptors in the oxidation of their carbonaceous food source (electron donors). The reduction of chlorinated solvent molecules that are used as electron acceptors cleaves one or two of their chlorine atoms, leading to the sequential dechlorination pattern observed in many contaminated aquifers. Several bacterially mediated anaerobic processes that lead to reductive dechlorination are discussed in detail in Section 1.3 of the protocol document (Suthersan, 2002). By injecting a degradable carbon source into the aquifer, the rate and extent of bacterial reductive dechlorination can be enhanced to levels that provide a cost-effective remedial method. These reductive dechlorination processes include dehalorespiration (in which reductive dechlorination is used for growth with CAHs serving as the electron acceptor) and cometabolic anaerobic biodegradation (in which the degradation does not yield a metabolic benefit to the bacteria). These cometabolic processes typically occur under either sulfate reducing or methanogenic conditions

In practice, ERD can be operated as an in-situ bioreactor that forms downgradient from a line of degradable substrate injection wells placed in a line perpendicular to groundwater flow. If sufficient carbon substrate is injected, oxygen and nitrate metabolism dominates near the injection line, while sulfate reduction, methanogenesis and reductive dechlorination zones form farther downgradient. The technology operates most effectively when groundwater is passing through the sulfate-reducing zone, still bearing a degradable carbon load that will support methanogenesis and reductive dechlorination.

A conceptual design of this process has been provided as Figure 2-2. This technology can be implemented in a variety of ways, including fixed, automated systems and mobile, manually controlled systems (See also Sections 4 and 6 of the protocol document [Suthersan, 2002]). The particular system used in this demonstration was truck-mounted (see Figures 2-3 and 2-4 for a schematic and photograph of this system).

ERD technology developed from ex-situ biological reactor and precipitation technology, which has been routinely used for decades to treat a broad range of inorganic and organic compounds. However, some of these ex-situ processes involve addition of reagents, such as sulfide salts, which would be controversial to use in-situ. Efforts over the last 15-20 years have demonstrated that similar treatment approaches can be engineered in-situ. CAH biotransformation under anaerobic conditions has been studied for two decades at various scales (Vogel and McCarty, 1985; Parsons and Lage, 1985; Bouwer, 1993; and references cited therein). Researchers and remediation practitioners at ARCADIS recognized that biochemically-induced changes could be achieved without the need to inject potentially controversial reagents, and that naturally occurring mechanisms of attenuation could be enhanced.

In early 1994, when a commercial client requested an innovative remedial solution for chromate-impacted groundwater at a CERCLA site in Pennsylvania, ARCADIS chose molasses as a reagent to enhance these processes. In this case we avoided the technical, regulatory, safety and economic concerns associated with sulfide injection by using molasses to achieve reducing conditions. The Pennsylvania project clearly demonstrated that molasses IRZs could effectively produce controlled conditions required to remediate heavy metals. Subsequent projects have demonstrated the effectiveness of IRZs for remediation of CAHs and other organic and inorganic contaminants. Our experience has shown that molasses is not the only carbohydrate material that can be used for this purpose; other carbohydrates such as high fructose corn syrup and whey can also be effective. This approach has been accepted by regulators and has since been demonstrated in a wide variety of geological conditions with both high and low groundwater velocities. Enhancing CAH degradation using ERD has become an accepted practice in the last several years, but additional work remains to improve the design and optimize performance of ERD systems under varying conditions.

In addition to CAHs, ERD processes have a potential application to a wide spectrum of contaminants and co-contaminants such as:

- Chlorinated cyclic hydrocarbons, e.g., pentachlorophenol (PCP)
- Chlorinated pesticides, e.g., chlorinated propanes, lindane
- Metal precipitation, e.g., Cr^{+6} to Cr^{+3}; metal sulfide complexes of nickel and copper; metal-humic complexes of beryllium and other metals
- Other halogenated organic contaminants

2.1.2 Design Criteria

The key parameters that go into an IRZ/ERD system design include:

- Formation geochemistry (including the concentrations of electron acceptors such as dissolved oxygen (DO), nitrate, sulfate etc, pH and buffering capacity)
- Site-specific hydrogeology (including depth to water, saturated thickness, and hydraulic conductivity)
- Contaminant mass and form (dissolved, sorbed and free phase).

These parameters are discussed thoroughly in Sections 2 and 4.1 of the protocol document (Suthersan, 2002).

Ultimate design goals include contaminant removal rates and closure requirements (see Sections 1.2 and 3.1 of this report and Section 6.5 of the protocol document [Suthersan, 2002]). Interim design goals are set to ensure the creation of appropriate conditions for CAH biodegradation and may typically include these ranges for various field parameters (in this context, "monitoring wells" refers to those wells 1 to 3 months downgradient of the injection wells):

- pH - > 4.0 s.u. in the injection wells; > 5.0 s.u. in the monitoring wells
- DO - < 1.0 mg/L in both monitoring and injection wells
- Oxidation Reduction Potential (ORP) - > -400 mV and < -250 mV in the injection wells; < -100 mV in the monitoring wells. Note however that these ORP values should not be taken as absolutes since ORP is pH dependent. For sites where reducing environments are identified in the groundwater prior to initiation of reagent injections, a target goal of lowering the ORP by 200 mV in the injection wells and 100 mV in the monitoring wells should be employed.
- Total organic carbon (TOC) - >500 mg/L and < 9,000 mg/L in the injection wells and > 50 mg/L in the monitoring wells
- Specific conductance – order of magnitude increase in the injection wells; 20 to 50% increase in monitoring wells

To achieve those goals parameters that must be specified during system design include:

- Substrate to be used and initial dose rate
- Intended radius of influence/injection well spacing
- Injection and monitoring well layout (which may be a barrier, source zone or plume treatment system)
- Injection system type (manual vs. automated, conventional well vs. direct push etc)
- Systems to handle byproducts (which may include the injection of buffers or the use of ventilation systems under structures).

These design considerations are discussed at length in Sections 4-6 of the protocol document (Suthersan, 2002). Pilot testing is usually required and adjustment or "tuning" of the system during operation is critical. These topics are discussed in Sections 5 and 6 of the protocol document.

2.2 Previous Testing of the Technology

As of September 2002, ARCADIS has been involved with more than 130 IRZ sites, across five countries and 26 U.S. states. Thirty of these sites are full-scale implementations, five of which have achieved closure. The other sites are ongoing pilot applications, or Interim Remedial Measures, or they are completed pilot projects that are now in the full-scale design phase. The technology has successfully been applied to the following chlorinated compounds and metals:

- TCE, dichloroethene (DCE), VC, CT, chloroform (CF), chlorinated propanes, PCP, pesticides, trichlorofluoromethane, and perchlorate;
- Hexavalent chromium, nickel, lead, cadmium, mercury, and uranium.

Appendix A to the IRZ Protocol (Suthersan, 2002) includes a comprehensive table with information on ARCADIS IRZ sites for CAHs, as well as 15 case studies. Appendix A-1 of this document is an extensive bibliography of papers and book chapters published on this technology.

2.3 Factors Affecting Cost and Performance

Although application of IRZ using soluble carbohydrates can occur in a variety of hydrogeologic settings, there are certain conditions that are better suited for cost effective use of the technology. Existing conditions that are anaerobic or borderline aerobic/anaerobic but with insufficient TOC can be most rapidly treated. Conditions that are anaerobic and already have sufficient degradable TOC may not be aided substantially by addition of soluble carbohydrates. One of the most important criteria is hydraulic conductivity. Generally, hydraulic conductivity of the aquifer needs to be greater than 1 ft/day and when coupled with hydraulic gradients, groundwater velocities on the order of 30 ft/year, or greater, are desirable. Another important criterion is the pH, which needs to be initially in the range from about 5 to 9 in order to have an active microbial population. Site screening criteria and methods are discussed more fully in Section 2 of the protocol document (Suthersan, 2002).

The implementation of an IRZ project is a dynamic process which requires a detailed understanding of the site geochemistry and hydrogeologic conditions before implementation and as it changes as a result of pilot or full-scale implementation. This technology is most likely to be successful when there is considerable process monitoring during the initial deployment of the pilot test that allows for adjustment of reagent deliverability (strength and frequency). Where ERD has failed, or has required longer than expected treatment periods, it is usually the result of improper monitoring (the wrong parameters or the wrong frequency) or data evaluation in the early stages of the pilot test. TOC loading and induced gradients must be reviewed early in the pilot process to allow delivery rates to be increased (for greater spreading and greater TOC levels within the treatment area) or reduced (or a buffering agent added), if pH levels drop too quickly.

Similarly, the effects of reagent injections must be reviewed in the context of how the addition of aqueous solutions affect hydraulic gradients (i.e., mounding) and flow directions. Groundwater flow directions and gradients should be viewed both in a macro and micro scale before and during the demonstrations.

Once a preliminary determination has been made that IRZ is an appropriate technology option to consider for the site, a more detailed data set needs to be gathered. Information required to fully review a site for IRZ includes:

- Site specific geology and hydrogeology, including: fraction of organic carbon (F_{oc}) in the aquifer matrix, boring logs, predominant aquifer lithology, aquifer hydraulic characteristics, horizontal and vertical hydraulic gradient, groundwater velocity, and depth to water
- CAH concentrations and distribution, both current and historical, if available
- If available, data on general groundwater quality such as TDS, specific conductance, pH, dissolved organic carbon (DOC), carbonate and bicarbonate alkalinity, and general cation/anion scan [calcium, magnesium, sodium, potassium, chloride, sulfate, and nitrate]
- Any previously gathered biogeochemical data, including oxidation reduction potential (ORP), nitrate, sulfate/hydrogen sulfide, ferric/ferrous iron, dissolved oxygen, trace gases (including methane, hydrogen, carbon dioxide, ethane, and ethene)
- The site's situation (regulatory drivers, stage in the investigation/remediation process, clean-up goals and time frames, future plans for the site)
- Some brief historical information on the site (source of CAH, estimated date of release, and duration of release events)
- Maps showing the relationship of active operational areas (buildings, etc.) and impervious surfaces (roads and parking lots) to the contaminant plume(s).

Table 2-1 provides a comprehensive overview of cost elements associated with an ERD project.

In a general sense, with an IRZ system, the cost of the reagent material itself is relatively insignificant. When using reagents such as carbohydrates, the cost per pound of TOC delivered is as outlined on Table 2-2. The selection of a carbon substrate(s) will be primarily driven by overall reaction rates, which are, in turn, controlled by the site conditions. A goal should be to minimize overall project cost by minimizing the number of required injection points, the number of injection events, and reagent cost (Harkness, 2000). The physical characteristics of the substrate (i.e., phase and solubility) may also make certain substrates more suitable than others in particular applications.

The majority of the costs related to reagent injection include the labor associated with preparing the reagent mixture and injecting the material into the wells/points along with related costs (mobilization to the site, record keeping, preparation, etc.) Temporary equipment required for the injections includes a solution mixing/holding tank, a portable mixer, a transfer pump, and injection piping/hose. This equipment should be sized and consistent with use at the pilot test site and can be mobilized to each site in a conventional pick-up truck or by trailer. The mixer can be simple as a paddle, or agitation of the tank through truck movement. A nontoxic, non-reactive tracer, or pH buffers may also be included in the reagent solutions. Permanent equipment at the various injections wells includes a removable well seal for the injection wellhead, removable perforated diffuser tubing (to assure even reagent distribution along the screened interval of the well), and quick-disconnect fittings to allow easy attachment of the injection piping/hose to the diffuser tubes for the injection itself.

Budgetary limitations can often directly or indirectly affect design decisions such as source reduction versus plume-wide treatment. Appendix A of the IRZ Protocol (Suthersan, 2002) contains specific information regarding the technology application cost (capital and operation and maintenance) at a variety of sites in which ERD has been successfully applied. Based on our experience and analysis the two largest cost factors for ERD implementation are the injection well installation and the O&M associated with reagent injections. Three other factors that need to be given special consideration during design in order to develop the most cost effective approach for site remediation are:

- Plume Size to be Treated – This is the primary factor driving the cost of the technology as the larger the plume area to be treated the more wells are needed (drilling costs) and the more time it takes for reagent delivery.
- Depth of Target Zone – Drilling costs are the primary factor affecting overall technology cost. Therefore, deep contaminant settings and/or those requiring specialized drilling techniques (bedrock drilling, multiple conductor casings, etc.) can significantly increase costs. The depth to groundwater will define well design and contribute significantly to the capital cost of a full-scale system. The saturated thickness can also have an influence on cost, since there are practical limits on the maximum screened interval that can effectively be used in an injection well. Based on our experience, a 25-foot screened interval represents a practical limit for an injection point. Of course, this limit will be impacted by the heterogeneity of the subsurface lithology, hydraulic conductivity, and the resulting effects on groundwater flow characteristics. For example, if the lithology and resultant groundwater flow characteristics are such that there are variations in the flow characteristics within the target saturated interval, the use of multiple screened zones or multiple well points should be considered – even if the interval is less than 25 feet.
- Groundwater Flux through Zone of Treatment – Reagent injections also play a large role in overall technology costs. At sites in which there is a high groundwater flux, more substrate will be required, thereby increasing costs. In faster groundwater flow systems, the limited transverse dispersion in groundwater can limit the extent of the reactive zone created by an individual injection point. This is of particular importance in settings where drilling costs may be high, i.e., deep settings or complex geology. In such cases, an in-situ recirculation well can yield considerable cost savings over use of direct injection wells. This in-situ recirculation well concept aims primarily at delivering reagents in a cost effective manner while remediating larger, deeper contaminant plumes at sites with relatively high groundwater velocities.

2.4 Advantages and Limitations of the Technology

As late as 1998, conventional remediation options for sites contaminated with CAHs were considered to be air stripping, granular activated carbon adsorption, and ultraviolet oxidation (Nyer 1998). Most of these technologies are the ‘treat’ portions of conventional pump-and-treat systems where impacted groundwater is removed to the surface for treatment and discharge. Pump-and-treat is known as a conventional technology with limitations due to long term operations and maintenance costs, which can be prohibitively expensive. These limitations stem from the fact that many contaminants partition preferentially to aquifer solids rather than the water carrier fluid. This results in moving vast quantities of groundwater while removing increasingly smaller portions of contaminant mass with time. Established remediation methods for metals removal also employ groundwater extraction followed by ion exchange or chemical precipitation. Like pump-and-treat for CAHs, these remedial techniques are costly and require long periods of time to complete.

The primary advantages for IRZ using soluble carbohydrates can be summarized as follows:

- The *in-situ* process eliminates the need for transferring contaminant mass to other media (such as groundwater pumping and subsequent treatment with air stripping)
- IRZ processes have a potential application to a wide spectrum of contaminants and co-contaminants
- No ex-situ waste is generated
- The process usually uses electron donor sources that are typically easily accepted by regulators and the public
- The biologically mediated reactions involved can generally be driven by indigenous microflora
- The technology is flexible in application, yielding a spectrum of contaminant mass treatment options from passive/containment barrier applications to aggressive source area applications
- Promotes reduction of residual contaminant mass through desorption and disruption of the contaminant phase equilibrium
- Enhances natural attenuation processes
- Applicable to various geological settings and aquifer conditions
- Electron donor source is highly soluble and can move through both diffusive and advective processes into difficult lithologies such as fractured bedrock
- Systems can be designed with flexible operation approaches ranging from automated systems to manual bulk application
- Can be used in tandem with existing remediation systems to optimize performance
- Can be designed with minimal site and facility operation disturbance

All in-situ remediation technologies have an inherent limitation associated with subsurface conditions. The geology in which the technology is being applied will exert considerable control over remediation efficacy. Mass transfer and distribution rates in porous media are the primary factors influencing the efficiency of the IRZ technology using soluble carbohydrates. This can be compensated for to a great extent by a complete understanding of the geochemical and hydrological conditions of the aquifer system to be treated. A good conceptual model of the aquifer will produce a more effective IRZ design. Potential limitations to the application of the IRZ technology using soluble carbohydrates can be summarized as follows:

- Excessive depth of contamination tends to raise costs
- Low permeability aquifers require more injection points

- High permeability aquifers with high groundwater flows require an excessive amount of reactant to establish a reducing environment due to dilution and oxygen recharge
- Heterogeneous lithology, which incorporates preferential flow paths, can limit the distribution of the injected substrate
- Limited porosity of contaminated media such as fractured bedrock minimizes the propagation of treated area
- Biological fouling of injection wells or aquifer resulting from reagent injection is theoretically possible but is rarely observed in practice
- Systems with large amounts or influxes of electron acceptors such as oxygen, nitrate or soluble iron can require large doses of substrate, however, substrate cost is typically a small fraction of the total project cost
- Potential production of excessive quantities of reduced gases such as methane can be problematic in the vicinity of confined structures. Also, production of byproduct organic compounds containing reduced sulfur or nitrogen, including hydrogen sulfide is possible.
- Molasses in its pure form contains concentrations of several metals. In a dilute mixture, as is typically used in IRZ applications, the concentrations have been below regulatory standards. Injected metals did not produce secondary water quality issues in this demonstration (see Section 4.3.5). However, this is a potential issue that should be considered in the design phase.
- Longer lag times prior to effective treatment are noted in low concentration plumes
- Intermediate products such as VC can be formed, however proper system design can ensure their further degradation
- Highly brackish aquifers can pose problematic microbial ecology
- Effectiveness on large pools of free-phase dense, non-aqueous phase liquid (DNAPL) has not been proven although it does appear to be applicable to sorbed or residual DNAPL
- If not carefully controlled, fermentation effects of excessive molasses loading can create conditions conducive to formation of aldehydes, ketones and mercaptans, which, however, can then be further degraded biologically. Excessive fermentation can also decrease pH and potentially mobilize naturally occurring metals.

These potential limitations are general guidelines to be considered when evaluating potential sites for ERD treatment. Site-specific constraints should be considered for all remediation technology options.

Other innovative alternatives for the treatment of chlorinated aliphatic hydrocarbons in the saturated zone include chemical oxidation with permanganate or Fenton’s reagent as well as various forms of reductive iron barriers.

3. Site/Facility Description

3.1 Performance Objectives

This demonstration is the first of a series of Environmental Security Technology Certification Program (ESTCP)/Air Force Center for Environmental Excellence (AFCEE) funded demonstration projects that aim to evaluate the efficacy of the IRZ/ERD technology to remove CAHs from the impacted groundwater in a range of geologic conditions and CAH concentrations. A second demonstration project at Vandenberg AFB has been funded and will be reported in a separate document.

Primary and secondary performance objectives, as established and discussed in the demonstration plan, are presented in Table 3-1.

3.2 Selecting Test Site

The Hanscom AFB site chosen for this demonstration was selected and proposed based on ARCADIS' review of obtainable site characterization data. Most existing DoD-wide databases of sites are limited in the depth of information available, i.e., (1) they treat bases as a whole but do not provide information specific to each site or operable unit or (2) types of contaminants are listed but not concentrations or closure standards. Thus, candidate sites were obtained in a non-systematic, networking-based approach. Information on candidate sites was solicited from ARCADIS, AFCEE, ESTCP and the Army Environmental Center staff. The qualifying criteria used during this initial site review included the following issues:

- Depth (size) of the contaminated aquifer requiring treatment – generally, this is of little technical significance, however, there are cost implications as depth increases
- CAH concentrations preferably exceeding 10 times the treatment standard or 3 times the treatment standard AND 10 times the detection limit to allow easy detection of the effect of the treatment
- Site must exhibit at least moderate hydraulic conductivity ($K>10^{-4}$ cm/sec or 0.3 ft/day)
- Site should have completed an initial investigation, or be in the remedy selection process or have an operating pump-and-treat system in place
- Site should have no DNAPL present or DNAPL remedy selected/successfully implemented with ERD implementation as a polishing remedy. This was suggested just as a requirement for the initial demonstration site. The presence of DNAPL would represent a continuing source of dissolved CAHs that would complicate efforts to monitor the progress of the IRZ technology in a short-term demonstration. As discussed later, although the demonstration area was initially believed to be downgradient from the source, it was later determined to be a source zone, although no clear evidence of free phase DNAPL has been discovered.
- Available sulfate mass must correspond to the microbiology that is appropriate for the type of ERD desired. Aquifers that are high in sulfate may not be conducive to developing microbiology that is appropriate for CAH remediation

During the review, site hydrogeology and other data were examined. Existing data on CAH contaminant and intermediate breakdown product concentrations and the site's current regulatory status were considered during the initial site screening. Candidate sites were chosen from a grouping of approximately 25 DoD sites with CAH impacts. These 25 sites do not constitute an exhaustive list of DoD sites that could benefit from the implementation of the ERD technology. Sites were selected based on a combination of factors. One important factor was adherence to technical constraints of ERD technology discussed above. ARCADIS also considered the economic issues that impacted our ability to provide a cost effective demonstration program at a number of DoD sites. Thus, factors such as depth to the water table and geographical location (proximity to one of ARCADIS' offices) were important in site selection. Geographical factors and depth to the water table are not typically involved in choosing to implement the ERD technology from a technical prospective. Lastly, the sites were judged as to whether they were good "field laboratories" in which ARCADIS could implement the ERD technology and interpret the results in a manner consistent with the goals of an ESTCP/AFCEE demonstration project. Sites with extremely low groundwater velocities were eliminated as incompatible with a short-term field program although the technology can be applied at sites with low velocities as long as the aquifer hydraulic conductivity is reasonable.

Site selection criteria for ERD systems have been broadly described in Section 2 of the protocol document (Suthersan, 2002). Although application of ERD using soluble carbohydrates can occur in a variety of hydrogeologic settings, there are certain conditions that are better suited for cost effective use of the technology. One of the most important criteria is hydraulic conductivity. Generally, hydraulic conductivity of the aquifer needs to be greater than 1 ft/day and when coupled with hydraulic gradients, groundwater velocities on the order of 30 ft/year, or greater, are desirable. Another important criterion is the pH, which needs to be initially in the range of about 5 to 9 in order to have a microbial population suitable for microbial activity. Other general site selection criteria include:

- No large quantities of pooled DNAPL, or DNAPL remedy selected/implemented but a polishing step needed. (Note that the application of this technology for moderate amounts of, for example, emulsified or sorbed free product is an active area of technology development. This is possible, but not as rapid as applications for dissolved/sorbed CAH contamination). Elevated concentrations of solvents may act as toxic inhibitors to biodegradation as well, especially for sites where the release is relatively recent (i.e., within 1 to 3 years) and the in-situ biological community has had little time to adapt and diversify.
- Sites that show some evidence of slow biodegradation, including those "stalled" at DCE and VC are desirable.
- The depth of the plume is also a factor in determining the cost effectiveness of an in-situ approach. The capital expense related to installing multiple injection wells in deep settings (greater than 50 feet below ground surface [bgs]), or in installing recirculation wells across thick homogenous settings needs to be compared to the costs associated with competing technologies.

Existing redox conditions that are anaerobic or borderline aerobic/anaerobic but with insufficient TOC can be most rapidly treated. Conditions that are anaerobic and already have sufficient degradable TOC may not be aided substantially by addition of soluble carbohydrates.

Table 3-2 summarizes evaluation criteria for implementing IRZ technology at Hanscom per established site screening parameters.

Based on the available geologic/hydrogeologic and groundwater chemistry data, the ability to successfully implement ERD technology at Hanscom Field appeared favorable. Calculated groundwater velocities and aquifer hydraulic conductivities (the ability to deliver reagents) at the site both appeared to be within acceptable ranges.

The long-term strategy for remediation of the CAH impacts at Hanscom Field includes natural attenuation. ERDs could be used in tandem with the current pump and treat approach, limiting the life span and high costs associated with pump and treat, enhancing natural attenuation of CAHs, and ultimately shortening the time needed to clean up the site. ARCADIS had already established a presence at Hanscom Field with the installation and startup of the vacuum enhanced recovery system for the bedrock aquifer near Site 1. Base representatives had expressed interest in implementing IRZ technology in this same area. Furthermore, the Base has an excellent relationship with the regulators at the Massachusetts Department of Environmental Protection, who had earlier expressed that they were “fully supportive” of a pilot demonstration of ERD technology at Hanscom field.

Field tasks for the pilot demonstration at Hanscom Field were handled by the ARCADIS office in Lowell, Massachusetts. The Lowell office is within 30 minutes from the site. Furthermore, the Lowell office had experience implementing ERD technology.

In summary, upon initial review, Hanscom AFB provided a fairly standard site for IRZ implementation. In retrospect, several factors complicated its use as a demonstration site, including variable gradient/potentiometric surface and the relative complexity of its subsurface lithology. However, a successful demonstration was conducted.

3.3 Test Site Description

3.3.1 Site/Facility Description

Hanscom AFB is located in Middlesex County, Massachusetts, approximately 14 miles northwest of downtown Boston. The Base occupies about 800 acres in the Towns of Bedford, Concord, Lexington, and Lincoln. Hanscom AFB is home to the Electronics Systems Center (ESC), a dynamic nucleus of research and development. ESC is the Air Force’s acquisition and development center for world-class command and control systems. Hanscom Field, located adjacent to and north of the Base, is a civilian airport operated by the Massachusetts Port Authority (Massport) and the Federal Aviation Authority. Prior to 1973, Hanscom AFB leased the runways and flight line of what is now Hanscom Field from the Commonwealth and the primary mission of Hanscom AFB was the operational maintenance of fighter aircraft and research and development (R&D) support. Historical operations at the Hanscom AFB/Hanscom Field complex involved the generation, use, and disposal of numerous hazardous substances, such as petroleum products, paint, and chlorinated and aromatic solvents. As a result of waste disposal and resource management practices during the period that the Hanscom AFB had a flying mission, the groundwater and soil in areas of Hanscom AFB and Hanscom Field became contaminated. In response, the Air Force included Hanscom Field sites in its environmental restoration program. Initial field investigations of the airfield sites commenced in the summer of 1982. The site was listed on the National Priorities List in May 1994.

The area of interest for the demonstration of ERD technology at Hanscom AFB is downgradient from Site 1. The source area for Site 1 is located on Hartwell's Hill, northwest of the overrun for Runway 23 and southeast of Hartwell Road, as shown in Figure 3-1. There are no aboveground structures in this portion of the AFB. According to Haley and Aldrich (1988), the Site was known as Fire Training Area II, and was reportedly used from the late 1960s through 1973 by the Hanscom AFB Fire Department for training exercises and for research on pyrokinetic materials. Fire training exercises consisted of collecting drummed waste oils, solvents, paint thinners and degreasers from around the Base and transferring them to an aboveground tank on-site. These chemicals were dumped into a pit, ignited and then extinguished. CAHs have been detected in groundwater in a narrow plume which extends from the source area at Site 1, southeastward under the overrun for Runway 23 and through the area where the RAP1-6 well cluster is located (see Figure 3-2). Thus SIC codes 9711C and 4581 are applicable.

3.3.2 Site/Facility Characteristics

3.3.2.1 Geology and Hydrogeology

Hanscom Field is situated on the southern edge of a glacial lake bed known as Lake Concord, which was filled with sediment during the last phase of glaciation in the region. The overburden beneath the site consists of an upper glaciofluvial unit comprised primarily of fine sand; a middle lacustrine unit consisting primarily of interbedded silt, clay, and fine sand; and a lower glacial till unit comprised primarily of unstratified dense sand, silt, and clay. The boring logs for the RAP1-6 well cluster, within the focus area of this study, show the bedrock surface at approximately 50 feet bgs, with the upper and lacustrine units each approximately 15 feet thick, and the lower till unit approximately 20 feet thick. The underlying bedrock is comprised primarily of granite, with lesser amounts of diorite and gneiss. Cross-sections of the demonstration area are provided in Figures 3-3 and 3-4.

The area in the immediate vicinity of Site 1 is underlain by 18 to 25 feet of glacial till overburden that rests directly on granitic bedrock. The till typically consists of very dense, coarse to fine sand with variable amounts of silt, fine to coarse gravel, cobbles and boulders. Beneath the till, the bedrock surface slopes downward in an east-southeasterly direction from Site 1 towards the RAP1-6 well cluster. The bedrock surface drops an average of about 1 vertical foot for each 26 horizontal feet (Haley & Aldrich 1988). The glacial till layer that exists at ground surface at Site 1 grades into a more permeable, less dense, sandy till, interlayered with a denser, gray till near RAP1-6T. This lower sandy till comprises the "lower aquifer" described by Haley & Aldrich (1988). On top of the lower sandy till is a layer of stiff, laminated, glaciolacustrine silt with clay of varying thickness. Overlying the glaciolacustrine layer are glaciofluvial deposits of the "unconfined aquifer" described by Haley & Aldrich (1988). The unconfined aquifer material generally consists of brown, medium to fine-grained sand of medium to high density.

In-situ permeability tests had been completed for several wells in the lower (glacial till) aquifer near RAP1-6T. Hydraulic conductivity values for the lower aquifer range between 3 ft/day to 48 ft/day, and average 26 ft/day (CH2M Hill, 1997). Based on groundwater elevation contour maps, the hydraulic gradient of the lower aquifer in the vicinity of RAP1-6T was estimated at 0.006, and the effective porosity of the lower aquifer materials was estimated at 20 percent (CH2M Hill, 1997). Based on these data, the groundwater flow velocity in the lower aquifer was estimated at 0.8 ft/day, or approximately 290 ft/yr.

Groundwater at the site can be found in three distinct aquifers. The upper glaciofluvial unit comprises a shallow, unconfined aquifer. Groundwater flow velocity in this water-bearing zone is approximately 1,100 feet per year. The clays and silts in the middle lacustrine unit have a semi-confining effect on the aquifer in the underlying lower till unit. Groundwater flow velocity in the lower till unit is approximately 300 feet per year. The third aquifer beneath the Site consists of the fractured granitic bedrock. Estimating groundwater flow velocities in bedrock can be difficult due to preferential flow through individual fractures. By considering the bedrock beneath the site to be the equivalent of a porous medium, groundwater flow velocity is estimated at 120 feet per year. However, actual groundwater flow velocities in bedrock are expected to vary significantly, being higher near individual fractures or fracture zones, and lower in relatively unfractured zones (CH2M Hill, 1997).

The depth to groundwater has ranged from about 7 to 9 feet bgs in well RAP1-6S in the unconfined aquifer, from 4.5 to 8.5 feet bgs in RAP1-6T in the lower aquifer, and from 2 to 9.2 feet bgs in RAP1-6R. Vertical hydraulic gradients at this location would normally be upward from the lower and bedrock aquifers to the unconfined aquifer. However, due to pumping from nearby lower and bedrock aquifer interceptor wells, the gradients are reversed. Also, the groundwater elevations in all aquifers have generally been lower since mid-1991, apparently due to the groundwater collection and treatment system placed in operation in the spring of 1991.

Well cluster RAP1-6 is located approximately 36 feet from the access road that parallels the overrun for Runway 23. Approximately 10 feet beyond the wells is a chain-link fence, behind which is a drainage channel (see Figures 3-5 through 3-7). The channel has steep banks with approximately 20 feet of relief from the top of the slope to the bottom of the channel. The channel is approximately 40 feet wide from the top of the slope at either side. The channel is used to convey stormwater from the runways to a wetland area to the northeast. Beavers have built dams downstream across the drainage channel, which have backed up water through the length of the channel.

According to the Solute Transport Model Setup and Calibration Report completed by CH2M Hill in December 1997, natural regional groundwater flow direction is to the east/northeast. In the areas of Site 1 and Site 2, contaminant migration would have taken place under natural groundwater flow from some time in the early 1960s until 1991. This is manifested by the plume orientations, which may predominantly reflect historical groundwater flow patterns rather than current ones. This is significant because current groundwater flow patterns are complicated by the number of pumping influences at the site. These pumping influences create more radial flow patterns from the west to the east and from the southwest to the northeast. A potentiometric surface map from 1998 (Figure 3-8) shows predominant groundwater flow in the demonstration area from the northwest to southeast (bending eastward in the vicinity of RAP1-6T). Monitoring well locations were intended to be immediately downgradient of the injection well and potentiometric surface data was carefully monitored over the demonstration period to account for observed shifts in gradient.

3.3.2.2 Climatology

The climate of the greater Boston area is temperate, with an average monthly low temperature of 28.6 degrees Fahrenheit (°F) in January, and an average high monthly temperature of 73.5 °F in July. Average annual precipitation in the form of rain, hail and snow is 41.5 inches, with November the wettest month and July the driest.

3.3.2.3 Distribution of CAHs and Current Pumping Remedy

Residual CAHs remain beneath Site 1, in the adsorbed and dissolved phases, and also potentially as residual DNAPL. CAHs have been detected in groundwater in the unconfined, lower, and fractured bedrock aquifers.

Groundwater samples have been collected for laboratory analysis of CAHs from the RAP1-6 well cluster since 1986. A summary of the groundwater monitoring data from nearby monitoring wells in the lower and bedrock aquifers is provided in Table 3-3. The predominant CAHs detected have been TCE and 1,2-DCE. Other commonly detected CAHs include VC, tetrachloroethene (PCE), 1,1,1-trichloroethane (1,1,1-TCA), 1,2-dichloroethane (1,2-DCA), 1,1,1- dichloroethane (1,1,1-DCA), and 1,1- dichloroethene (1,1-DCE).

No biogeochemical analyses was conducted prior to selection of this site as a candidate, but a baseline round of analyses was conducted by ARCADIS prior to the decision to go forward with the demonstration.

<u>Lower Till Aquifer (Target Zone)</u>

The semi-confined aquifer in the lower till unit was targeted for the pilot demonstration. This aquifer contains elevated total volatile organic compound (TVOC) concentrations ranging from a low of 3.2 μg/L in RAP1-1T to a high of 5,400 μg/L in RAP1-6T. Historic sampling data for the Site indicates that this water-bearing unit contains “source” CAHs such as TCE and 1,1,1-TCA, as well as biotic degradation compounds such as *cis*-1,2-DCE, 1,1- DCA, and VC. The presence of 1,1-DCE further suggests the abiotic transformation of 1,1,1-TCA via elimination reactions (1,1-DCE can then be reductively dechlorinated to VC and ethene). Historical trends in the concentration at RAP1-6T are presented and discussed in Section 4.3.3.3.2 of this report.

<u>Bedrock Aquifer</u>

The bedrock aquifer typically has the highest TVOC concentrations, ranging from a low of 2.5 μg/L in RAP1-1R to a high of 589,000 μg/L in RAP1-3R. Well RAP1-3R is located within the area of influence of the Vacuum Enhanced Recovery (VER) system operating at Site 1, substantially upgradient from our demonstration zone. As with the lower lacustrine unit, historic sampling data indicates that wells installed in the bedrock contain source CAHs and degradation compounds such as TCE, 1,1,1-TCA, 1,2-DCE, 1,1-DCE, 1,1-DCA, and VC. Based on dissolved-phase concentrations and the configuration of the bedrock surface, it is believed that there may be residual DNAPL along the bedrock/overburden interface under (and downgradient of) the original release locations at Site 1. Current pumping at IW-6 and operation of the VER system is intended to capture this source material so that the downgradient recovery wells (IW-2, IW-3, and IW-4) can contribute to cleanup of the plume. In bedrock well RAP1-6R, total CAH concentrations have ranged from a high of 8,100 μg/L in June 1996 to a low of 2,110 μg/L in February 1991, and concentrations of VC have increased substantially between 1986 and 1998.

3.3.2.3.1 Existing Groundwater Remediation

The current remedy at Hanscom Field is comprised of pump and treat collection trenches and recovery wells, coupled with a VER demonstration/pilot in the source zone. Both Site 1 and Site 2 have collection trenches which have essentially cleaned up the shallow unconfined aquifer, resulting in very limited areas of residual impact around the original source locations (TVOC concentrations in the shallow water-bearing unit identified during the May 1998 sampling event range from below laboratory detection limits to a maximum of 760 μg/L). The lower till and bedrock aquifers contain four “interceptor” recovery wells installed along the Site boundary (wells IW-1 through IW-4), two additional recovery wells installed just downgradient of the source areas at Site 1 (IW-6) and Site 2 (IW-5), and four VER wells installed just downgradient of the source area at Site 1.

A pilot test of permanganate oxidation was conducted in the VER area in 2001. According to Tom Best (personal communication, 2002) “We started injections in June 2001. 2 of the 3 injections (June & October) were in bedrock wells and the 3rd was in the surface/lower aquifer well (RAP1-3S) in August 01. However, by October 01 the water table (had) dropped into bedrock for a couple of months. When it got back up in(to) the till the permanganate was gone.” Thus since most of these injections should not have affected the lower aquifer, and this area is two to three years’ travel time upgradient of the demonstration zone, it was not expected to influence the demonstration results.

The primary objective of the collection trenches and interceptor pumping wells is containment of the plume, while the four VER wells are intended to focus on source removal. The groundwater remediation system at Site 1 is part of a pump-and-treat system that operates at three “sites” at Hanscom. Recovered groundwater from all three sites is piped to a large-capacity treatment system that uses two stripping towers in series to remove the CAHs and granular activated carbon to treat the off-gas. The average groundwater flow rate for the Site 1 collection system is 20 to 25 gallons per minute. Annual Base-wide groundwater volumes treated have ranged from 50 million gallons to 148 million gallons over the period 1991-2002 (Hanscom AFB, 2002).

3.3.3 Site/Facility Maps and Photographs

A drawing showing the features of the demonstration zone in the vicinity of RAP1-6 well cluster, including the overrun for Runway 23, the drainage channel, and nearby monitoring wells, is shown on Figure 3-9. Figure 3-8 also shows the groundwater elevation in the lower aquifer based on groundwater elevation measurements taken by Haley & Aldrich in May 1998. Figure 3-2 shows the total CAH distribution in nearby monitoring wells in the lower aquifer from the May 1998 groundwater monitoring event.

Site photographs as discussed above are provided as Figures 3-5 through 3-7. Figure 2-4 shows the injection well in-service.

3.3.4 Conceptual Site Model

The initial conceptual model for this site included groundwater transport of dissolved-phase CAHs from the source area at Site 1 to the area around the RAP1-6 well cluster and beyond to the southeast. The initial releases occurred when waste solvents and oils were placed into burn pits at Fire Training Area II. These contaminants infiltrated downward by gravity through fractures and pore spaces in the till until they reached the water table. Water table fluctuations at the source area ranged from 10 feet above, to just below the till/bedrock interface. Below the water table, the DNAPLs continued to move downward by gravity until they could no longer migrate through fractures due to decreasing fracture apertures. The DNAPLs pooled in low spots at the till rock interface where there was little fracturing, but also entered bedrock fractures and migrated down into the bedrock.

At the till/bedrock interface is a relatively high permeability zone consisting of basal gravel or highly weathered bedrock. The high permeability zone, combined with the sloping bedrock surface, allowed migration of DNAPL and dissolved-phase contaminants to the southeast towards the overrun for Runway 23 and well cluster RAP1-6. Groundwater transport modeling by CH2M Hill suggested that DNAPLs may have migrated along a bedrock trough from Site 1 towards well cluster RAP1-6. However, even though there are relatively high total dissolved CAH concentrations in monitoring wells downgradient from Site 1, there were no analytical data or visual observations to confirm that DNAPLs have migrated as far as the RAP1-6 well cluster prior to the start of this demonstration. Concentrations of 1,2-DCE and TCE in wells near RAP1-6 were less than 1% of the solubility limit of those compounds, and no DNAPLs have been observed in any of the monitoring wells screened in the lower or bedrock aquifers in this area.

Remedial pump-and-treat systems operating since 1991 have contained most of the migration of dissolved or non-aqueous phase CAHs, especially in the unconfined shallow aquifer, in which CAH concentrations are now in the low μg/L range. Between 1991 and August 1997, downgradient migration in the lower and bedrock aquifers continued and was enhanced by the interceptor wells of the treatment system, which recover groundwater from the lower and bedrock aquifers along the Hanscom Field boundary with the Town of Bedford to the north-northeast. In August 1997 a bedrock interceptor well in the immediate vicinity of the Site 1 source area was placed in operation to contain the CAHs near the source area. This effort has subsequently been augmented by a four-well VER system and four additional lower and bedrock aquifer interceptor wells, all in the immediate vicinity of the Site 1 source area on Hartwell's Hill (about 800 feet or nearly 3 years groundwater travel time upgradient of the IRZ demonstration zone).

Ongoing pump and treat actions and natural attenuation appear to be precluding further off-site migration of contaminants and reducing both on-site and off-site concentrations. The overall remedial goals for the site are to achieve cleanup goals consistent with current and foreseeable future uses. For groundwater, the long-term cleanup goal is to achieve drinking water standards, since this site lies within an area classified as GW-1 (i.e., potential drinking water supply) by the Massachusetts Department of Environmental Protection (MADEP). For the CAHs detected at this Site, the MADEP's GW-1 Standards are equivalent to the U.S. EPA's Maximum Contaminant Levels (MCLs). Despite the fact that operation of a pump and treat system around the clock since 1991 has succeeded in substantially reducing TCE concentrations, TCE at Sites 1 and 2 is still well above the current MCL (see Figures 3-10 and 3-11 abstracted from Hanscom AFB, 2002) and may have reached an asymptote. For this demonstration project, the objective was to determine if natural attenuation processes could be enhanced to accelerate the progress towards the site-wide remedial goal.

3.4 Pre-Demonstration Testing and Analysis

As discussed in Section 3.3.2.1, the demonstration area is underlain by an unconfined upper aquifer and a semi-confined lower aquifer (the target zone for the demonstration), both consisting of glacial deposits, and separated by a stiff, laminated layer composed of glaciolacustrine silt with clay. The lower aquifer rests directly on bedrock at a depth of about 50 feet. We have prepared cross sections of the demonstration zone and vertical correlations of the installed wells (Figures 3-3, 3-4, and 3-12). These show that the injection well and most of the monitoring wells span the majority of the thickness of the lower aquifer – which is a tightly packed, poorly sorted till.

Pretreatment soil characterization in the lower aquifer during well installation (Table 3-4 and Appendix A-2) showed relatively low concentrations of soil TOC (<2%) and consequently low concentrations of sorbed TCE (<7 ppb), *cis*-1,2-DCE (<30 ppb) and VC (<11 ppb). The only other organic detected was a trace of acetone. The grain size analysis showed almost all the samples to be silty sand mixed with gravel which is consistent with the previous discussion of this zone as a till.

Prior to this demonstration project, a previous site consultant had conducted a modeling effort. In order to make the model reproduce the observed groundwater concentrations it was necessary for the modelers to postulate the presence of a source in the vicinity of well RAP1-6T (Figure 3-13), (CH2M Hill, 1997). According to Mr. Tom Best at Hanscom AFB, information from a former employee at the Base suggested that solvent disposal/fire training activities were conducted at one point on this southeast side of the runway. Previous attempts to locate a source zone in this area through vapor probing were unsuccessful. However, when ARCADIS installed five additional wells in June 2000, the existence of this source area was confirmed by a clear increasing trend in groundwater concentration in the lower aquifer in this area (Figure 3-14). As shown on that figure, the total volatile organic compound (VOC) increased dramatically from northeast to southwest in the lower aquifer in the immediate demonstration area before the demonstration. They were:

- 125 µg/L at B239-MW
- 2,700 µg/L at the well that would be used as the injection well later
- an average of 6,130 µg/L at the transect of monitoring wells that includes RAP1-6T
- an average of 8,060 µg/L at the transect that that includes IRZ-2 and IRZ-3 (note that IRZ-5 was not installed until after the demonstration began).

Other pretreatment physical characteristics of the subsurface at this site are listed in Table 1-1. Before treatment, the TCE in the lower aquifer at the RAP1-6 well cluster was fairly constant over 15 years, averaging between 1,000-2,000 µg/L with elevated levels of both *cis*-1,2-DCE (2,000-5,000 µg/L range) and VC (500-1,300 µg/L range) (see a more detailed discussion in Section 4.3.3). The site was moderately anoxic/reducing (DO <1.5 mg/L, ORP typically 0 to -50 mV) with a near neutral pH in the range of 6.0 to 6.5 prior to treatment. Note also that the ethene and methane level in IRZ-1 and these other neighboring wells was low (Figures 4-30, 4-32), and hydrogen sulfide was low (Figure 4-40). A summary of the initial baseline geochemical characteristics of the site is provided as Table 3-5. Notable are the relatively low concentrations of nitrate, sulfate and DO along with some evidence of dissolved methane.

The behavior of chlorinated solvent plumes with respect to reductive dechlorination has been categorized into three types (USEPA, 1998). Type 1 behavior occurs in the presence of anthropogenic carbon, and results in the rapid degradation of the more highly chlorinated solvents, provided that anaerobic conditions and an adequate supply of carbon substrate exist. Type 2 behavior is similar to Type 1, but is driven by a relatively high concentration of biologically available natural organic carbon rather than an anthropogenic carbon source. Biodegradation is generally slower with Type 2 than with Type 1 conditions. In both cases, the role of competing electron acceptors and the fate of VC are variables to be considered. Type 3 behavior dominates where little carbon is available and conditions are aerobic, or where the microbial community is incapable of chlorinated solvent biodegradation. Reductive dechlorination does not occur under Type 3 conditions, but VC may be oxidized in an aerobic environment. In this classification system Hanscom appears to be a type 1 site. Clear evidence of the first stage of degradation to DCE has been observed before treatment. This may be a site that is “stalled” at DCE although some VC production is probably also present under pretreatment conditions. Although relatively little TPH data has been collected at this site since they are not primary risk drivers, petroleum hydrocarbons were known to be released in substantial quantities in fire training activities at this site and were found at the site 1 source area on Hartwell’s Hill (personal communication with Tom Best 2001). A recent National Academy of Sciences report (2000) points out that petroleum hydrocarbon can not always be relied upon as a long term electron donor for natural attenuation because they are often consumed over time before the CAH contamination is fully attenuated. TOC in the pre-injection baseline round ranged from 3 to 6 mg/L, suggesting that the amount of degradable carbon present was limited. Complete and efficient degradation would not be expected under these circumstances – that are probably not methanogenic or sulfate reducing but rather probably predominantly denitrifying or iron reducing. As shown in Table 1-1 of Suthersan, 2002 (reprinted from various ITRC sources), TCE degradation under these conditions has been observed on previous occasions but DCE and VC treatment has not. This suggests this site might indeed be “stalled” at DCE and VC. Thus although only one pretest round was available at IRZ-1 we have an internally consistent picture of the starting conditions that is also in agreement with our overall theoretical understanding of these processes developed based on experience at other sites and in the literature (Suthersan, 2002).

3.5 Testing and Evaluation Plan

Operational and experimental methods for the ERD demonstration from system start-up through demobilization are discussed in this section.

3.5.1 Demonstration Installation and Startup

Physical setup for the Hanscom AFB system was minimal. Permanent equipment was limited to wells, with a removable well seal with fittings on the injection well to allow for connection. Utility requirements were limited to a source of potable water from mixing of the molasses solution. The demonstration area, including pre-existing wells and new sample locations, is shown in Figure 3-9.

The temporary equipment required for the injections included the following: a 210-gallon solution mixing/holding tank, a gasoline powered transfer pump, and an injection hose. A schematic of the injection system is presented in Section 2.1. Start-up testing of injection system only included filling tank with water to check for leaks. The tank and associated pumps generally functioned without difficulty. All temporary equipment, molasses, and reagents (bromide tracer), were stored in an existing site building. A conventional pick-up truck was used to transport the equipment to the injection well for each injection event.

Steps required for each injection event included testing of pH in the injection well, consulting guidance provided by the project manager as to what injection to make depending on the observed pH, manual mixing of the reagent solution, connection of the injection system to the injection well, and pumping of the solution into the injection well followed by an injection of clean water into the injection well. Typically, either a single batch (200 gallons) or a double batch (400 gallons) of solution was injected. A single batch of reagent solution consisted of 20 gallons of food-grade blackstrap molasses, 180 gallons of potable water, and 113 grams of potassium bromide. Mixing of the reagent solution was accomplished by partially filling the 210 gallon solution tank with water, adding 20 gallons of molasses and 113 grams of potassium bromide to the tank, stirring the tank manually for several minutes with a polyvinyl chloride (PVC) stir rod, and then filling the tank to the 200-gallon mark with clean water.

Prior to each injection event, a small volume of groundwater (one to three well volumes) was purged from the injection well. The groundwater pH was then measured using a pH meter or litmus paper. Well pH was used to determine the volume of reagent solution to be injected. No other analyses were performed, except for process monitoring and groundwater sampling for technology effectiveness verification described in Section 3.5.7.

Once mixed, the solution tank and injection equipment was transported in a pickup truck to the injection well. Hoses were connected between the solution tank, transfer pump, and injection well. The system valves were then opened, the pump started and run until all of the reagent solution had been transferred to the well. If a double injection was planned, a second batch of reagent solution was mixed and injected using the same procedure. Following the injection of reagent solution, if a water push was to be injected, the solution tank was filled with 200 gallons of clean water, which was injected using the same procedure.

During the initial injection events the reagent solution injection proceeded at a rate of approximately ten gallons per minute at observed well head pressures of approximately 10 to 15 pounds per square inch gauge pressure (psig). However, due to assumed biological fouling of the injection well (discussed in the “System Maintenance” section below), injection pressures increased (due to higher flow resistance). In turn, the increased injection pressures apparently resulted in the degradation of the annular seal on the injection causing some leakage of reagent solution in the well vault during injections. As a corrective measure, injection pressures were controlled through a number of means to a lower pressure to prevent the leakage of the reagent solution.

During the final reagent injections, reagent and clean water injection flow rates were reduced to approximately one to two gallons per minute and pressures of two to three psig. Labor required for each injection at the initial injection rate, was approximately four to six hours for a single batch injection, with an additional one to two hours for a double injection. Due to the reduced flow rates toward the end of the demonstration, labor required for each event (exclusive of travel time to the site) had increased to approximately eight to ten hours for a single injection and twelve to sixteen hours for a double injection.

System Maintenance

Very little maintenance or repair work was required during the demonstration. A hose barb fitting on the injection system broke and was replaced on February 4, 2002. Additionally, the top of the injection well and its protective road box were damaged by a lawnmower as discovered on July 26, 2002. These items were promptly repaired and the top of well elevation was resurveyed as reported on October 16, 2002.

Given the enhanced biological nature of the in-situ remedy being used, there is some chance of biological fouling developing in and around the reagent injection wells (i.e., the well screen itself or possibly the well filter pack). However, given that the biological growth is anaerobic in nature, the actual mass of biological growth is typically minimal (as compared to biomass related to aerobic processes commonly observed in other remediation areas such as pumping wells or above-grade water treatment). In the case of reagent injection well fouling or plugging a typical remedy would be to surge the well using a well block to induce turbulence in the well and break up the biological mat.

During this demonstration, indirect evidence of biological growth in and around the injection well was observed as evidenced by a decrease in the maximum obtainable reagent injection rate after the first several injection events. This reduction in injection rate was also accompanied by an increase in injection pressure (i.e., resistance to flow created by the assumed fouling). In addition, the observation of increased injection pressures was coincident with the observation of a small amount of reagent solution leakage observed in the injection well vault. This leakage was observed to be coming from between the well casing and the surface seal.

Due to the nature of the injection equipment (e.g., a centrifugal pump without pressure regulation), the decreased flow rate caused a significant increase in injection pressure, which may have exceeded the soil fracture pressure. This in turn may have resulted in the creation of some fractures or voids in the annular seal for the injection well in turn resulting in the observed solution leakage at the surface.

Upon observation of the increased injection pressures and solution leakage, the corrective action employed by the field staff included either; a lowering of the injection pressure by reducing pump speed, lowering the injection pressure by throttling the pump using a flow control valve or in some cases performing the injections solely under gravity flow. Each of these actions were intended to minimize surface leakage. This avoided the capital cost and disruption of repairing or replacing the well.

Safety issues were limited to those associated with handling equipment (vehicles, pumps, hoses, fittings) in the field, and working with contaminated groundwater from wells. No hazardous materials were used in the injection solution or generated during operation of the system, with the exception of purge water from the wells.

3.5.2 Period of Operation

Dates of major events relevant to the demonstration are summarized in the table below. Dates of intermediate injections and monitoring events are tabulated in Table 3-6. A final round of groundwater monitoring to test for rebound effects is planned for November 2003.

Event	Date
Pre-Demonstration	
Initial investigations of Sites 1 and 2	Early 1980's
Installation of monitoring wells pre-dating demonstration	1985 (RAP1-6T cluster); 1996(B239-MW through B243-MW)
Demonstration	
Well-installations and soil sampling	May 2000 (IRZ-INJ, IRZ-1 through 4); May 2001 (IRZ-5)
Baseline groundwater sampling	June 2000
First substrate injection	October 11, 2000
Last substrate injection	October 9, 2002
Demobilization	October 9, 2002
Post-demonstration monitoring	Planned for November 2003

3.5.3 Amount/Treatment Rate of Material Treated

A total of forty-seven injections were conducted at Hanscom AFB since October 11, 2000. The final injection was conducted on October 9, 2002, and final sampling occurred on October 14 – 16, 2002, for a total of almost exactly 24 months of demonstration operation. Over this time, a total of 1,250 gallons of raw blackstrap molasses, 11,250 gallons of dilution water, 7,575 gallons of push water and 4,732 grams of potassium bromide have been injected into IRZ-INJ. The injection rate is shown in Figure 3-15. The average injection rate over the period of treatment was 139 lbs molasses/week. The chloride concentration of the molasses injection solution was measured on March 12, 2002 to be 1,500 mg/L.

3.5.4 Residuals Handling

No hazardous waste was generated during the setup and operation of this demonstration, except for soil (drill cuttings) generated during injection well and monitoring well installation, and purge water generated during well development and sampling. Purge water was disposed of in the on-site wastewater treatment plant. Soil cuttings were stored in 55-gallon drums, characterized and disposed of at a licensed hazardous materials disposal facility.

3.5.5 Operating Parameters for the Technology

A description of operating procedures and labor requirements for the ERD demonstration is given in Section 3.5.1. Carbon dosing was variable during the demonstration, as was the use of water injections to disperse the substrate. These parameters were determined on the day of the injection event based primarily on the pH measurement in the injection well, but also on more detailed process monitoring conducted at regular intervals during the demonstration. Section 4.3.2.1 contains a discussion of process monitoring parameters and process control throughout the project.

Performance monitoring (to assess technology efficacy) for this demonstration was conducted using high quality assurance analysis during three full sampling rounds and five abbreviated sampling rounds. Analytical parameters, methods and analysis locations/ organizations are specified in Table 3-7. Furthermore, records were kept of the color, odor and other readily apparent characteristics of the sampled groundwater. Additionally, some groundwater samples at Hanscom were analyzed on-site by the Base's gas chromatograph (GC), operated by an independent contractor. The SOP for this procedure is given in Appendix A-3.

3.5.6 Experimental Design

The experimental design for the project was established in the demonstration plan (ARCADIS, March 2000). In brief, the types of measurements made are listed below. Discussions on the methods and outcomes of each type of data collection are provided elsewhere, as cited.

- Soil characterization – Section 3.5.7.1.3 – Soil samples were collected once, during well installation and analyzed for the parameters listed in Table 3-8.
- Process monitoring – Sections 3.5.7.2, 4.3.2, 4.3.4 – In 13 periodic events, measured DO, pH, ORP, specific conductance, temperature and water levels. In addition, used field test kits to analyze for hydrogen sulfide and ferrous iron, and laboratory analysis for bromide and TOC.
- Full and abbreviated groundwater monitoring – Sections 3.5.7.1.2, 4.3.3, 4.3.5, 4.3.6.2, 4.3.6.3 - three full and five abbreviated sampling rounds were conducted, with analysis for the parameters listed in Table 3-7.
- Process control – Sections 4.3.2.1 – Varied carbon dosing and water pushes in 47 injection events based on continuous evaluation of groundwater monitoring data.

3.5.7 Sampling Plan

The project sampling plan was developed on the basis of ARCADIS' previous experience at commercial ERD sites and existing site data for the Hanscom demonstration area. The sampling plan is detailed in the project's demonstration plan (ARCADIS, March 2000), which also contains the project QAPP.

3.5.7.1 Sample Collection

Field methods are described in this section for well installation and sampling of saturated soils and groundwater.

3.5.7.1.1 Well Installation Procedures

The general area studied during the IRZ demonstration laid within an approximately triangular-shaped area between Monitoring Well B239-MW, Pumping Well No. 2 (BIW-2), and Pumping Well No. 4 (BIW-4) (Figure 3-2). The main focus area was around RAP1-6T, just west of the runway outrun, where one injection well and a series of new lower aquifer monitoring wells were installed (Figure 3-9). The target hydrogeologic unit was the basal sand, silt and clay glacial till unit that directly overlies bedrock at approximately 50 feet bgs in the demonstration area. The shape of the demonstration area and proposed well locations were determined based on the natural groundwater flow direction, the existence of the two downgradient pumping wells, as well as well placement limitations caused by the runway, a fence, and a drainage ditch located downgradient from the proposed injection well. Ten wells were used for data collection during the demonstration project: one (1) new injection well, five (5) new monitoring wells, and four (4) existing monitoring wells. Additional data was also collected from other nearby wells, when applicable.

The proposed injection well was installed immediately upgradient (relative to the originally-assumed southwest-to-southeast general groundwater gradient) from existing well cluster RAP1-6, which consists of wells RAP1-6S, RAP1-6T, and RAP1-6R, screened in the upper, lower, and bedrock aquifers, respectively. Existing monitoring well, B239-MW located approximately 400 feet upgradient from the proposed injection well was used as the primary background well. Downgradient wells used for demonstration monitoring included existing monitoring wells RAP1-6S, RAP1-6T, and RAP1-6R, and five new downgradient wells (IRZ-1 to IRZ-5) located as shown on Figure 3-9. Note that during the demonstration, the actual, measured direction of the groundwater gradient of the lower aquifer varied in response to various factors including pump-and-treat system operation (see discussion in Section 4.3).

The wells in the RAP1-6 cluster, including wells RAP1-6S (upper aquifer), RAP1-6T (lower aquifer), and RAP1-6R (bedrock aquifer), were installed in November 1985 for the US Army Corps of Engineers as part of a remedial investigation at the Base. Thus, these wells were present for use as groundwater monitoring wells during the demonstration project. RAP1-6T, which is of most importance to the demonstration project, is screened between about 30 and 45 feet below grade.

The installation of the injection well (IRZ-INJ) and four new monitoring wells (IRZ-1, IRZ-2, IRZ-3, and IRZ-4) was coordinated by ARCADIS and occurred in early-mid May 2000. The first of these wells installed was IRZ-2, located southeast of the drainage ditch, which was installed on May 3, 2000. The borehole for monitor well IRZ-2 was drilled using the hollow-stem auger techniques with 8-inch diameter augers. The boring was advanced to a total depth of 45 feet. The well screen was installed from 33.5 to 43.5 feet bgs (see Appendix A-4 for the relevant boring logs and well construction diagrams).

An attempt to drill IRZ-1 next was made on May 4, 2000, also using hollow stem augers. However, surging sand prevented the boring from progressing beyond 34 feet below grade. It was decided that a drive-and-wash drilling technique would be more appropriate for completing the remaining borings, and the borehole was abandoned. A replacement boring was installed on May 15 to 16, 2000, using the drive-and-wash technique and 6-inch diameter casing. The boring was advanced to refusal, and the well screen was set from 33.4 to 48.4 feet bgs. Wells IRZ-3, IRZ-4, and IRZ-INJ were installed during the period of May 5 through May 15, 2000, using the drive-and-wash technique. Borings for IRZ-3 and IRZ-INJ were advanced using 6-inch diameter casing, and well screens were set at 40 to 55 feet bgs and 34 to 49 feet bgs respectively.

Well IRZ-4 was installed initially using 6-inch diameter casing. However, a boulder was encountered at approximately 36 to 39 feet bgs, which could not be penetrated using the 6-inch casing. A 4-inch diameter casing was telescoped inside the 6-inch casing, and was successfully driven through the bolder. IRZ-4 was constructed with a 2-inch diameter well screen and riser, with the screen set at 36 to 51 feet bgs.

All of these wells were developed using a whacker pump and foot valve. 525 gallons of water were removed from IRZ-INJ with an improvement in the turbidity observed over the course of development. 250 gallons of water were removed from IRZ-1 and the water at the end of development was clear. 200 gallons of water were removed from IRZ-4, 125 gallons of water were removed from IRZ-2, and 85 gallons were removed from IRZ-3. The water was still slightly turbid at the end of development for wells IRZ-2, IRZ-3, and IRZ-4.

Well IRZ-5 was installed in May 2001, as a response to monitoring data suggesting that the flow direction from the injection well was toward IRZ-1 and missed monitoring wells IRZ-2, IRZ-3, and IRZ-4. A drive-and-wash drilling technique was used to advance a boring to a total depth of 53.5 feet bgs. The well screen was set at 38 to 53 feet bgs. Approximately 300 gallons of water were removed during subsequent well development.

Three sets of survey data were collected; after initial well installation, after well IRZ-5 was added in 2001 and after a well was damaged by a lawn mower in 2002. These data were used for potentiometric surfaces and mapping and are presented in Appendix A-5.

3.5.7.1.2 Groundwater Sampling

Groundwater Sampling and Field Measurements

Two main types of field parameter monitoring were conducted during the Hanscom AFB demonstration, high QA/QC events and low QA/QC events. High QA/QC field monitoring events were conducted, typically associated with groundwater sampling events during abbreviated and full process monitoring events, and used low-flow sampling methodology. During low QA/QC events, a down-hole sonde was used to make similar field measurements for process monitoring when full sampling was not require (i.e., before or during injection events). These lower QA/QC events provided very valuable feedback data on the biogeochemical conditions, to assist in making decisions on the amount of substrate to inject thus controlling the reactive zone. These lower QA/QC events provided additional time points to help analyze changes in the characteristics and extent of the IRZ.

Groundwater sampling methods during high QA/QC performance monitoring rounds, utilized low-flow, or micropurge procedures, consistent with EPA and AFCEE published protocols. The basic tenet of the micropurge technique is to collect groundwater from a discrete portion of the well screen at a rate which most closely replicates the natural recharge of groundwater from the formation into the well screen. This is accomplished by removing groundwater at low flow rates (typically between 100 and 500 ml/minute) while monitoring the water level within the well to ensure minimal (or preferably no) drawdown. While the well is being purged, field parameters are monitored at the well head using a flow through cell. DO, ORP, temperature, pH and specific conductance are monitored and recorded at ten minute intervals while the well is purged. When a minimum of three well volumes have been purged and these readings stabilize within 10% for three consecutive readings, the groundwater is considered to be representative of the aquifer (as opposed to stagnant water within the well) and groundwater samples for laboratory analysis are collected directly from the pump discharge at the surface. Depending on the depth to water and diameter of the existing wells at the site, different pumps may be utilized. At Hanscom, a low-flow, submersible, Redi-Flo pump was utilized.

During the demonstration period, a total of five high QA/QC abbreviated monitoring rounds, and three high QA/QC full monitoring rounds, including a baseline, midpoint and a final process-monitoring round, were conducted. The primary purpose of these events was to determine if the system was meeting its performance goals. The background full-monitoring round was conducted in June 2000, and the midpoint full-monitoring round was conducted in early May 2001. The final round was conducted October 14-16, 2002. Concerns about field equipment calibration during the mid-October monitoring round prompted a repeat of field parameter measurement “final” monitoring round, for field parameters only, on October 29, 2002. In addition, for comparison purposes a few samples were collected on October 29, 2002 for dissolved hydrogen using a different type of pump (see discussion below in this section). The final round of samples included secondary water quality parameters and will be followed approximately 12 months later by a “rebound” sampling round.

During the demonstration period, a total of thirteen low QA/QC process-monitoring rounds were conducted. The minimum parameter list for these events were pH, DO, specific conductance, and ORP. TOC and/or DOC were sampled when other indicators suggested the possibility of carbon overloading leading to fermentation. Additionally injection well pH was measured before every injection event and samples were obtained at intermediate time points for analysis by the Base’s field GC to obtain additional information about TCE and DCE.

The times for these sampling and field monitoring events were selected during the demonstration by the ARCADIS project manager and team leaders, in consultation with ESTCP and AFCEE. As expected, the process monitoring events were more frequent near the beginning of the injection program, when the optimum injection dose was being established. These parameters provided information on the efficacy of carbon delivery to the reducing zone and the redox condition of the zone. From this information, carbon injection regimes were fine-tuned and more involved monitoring events could be effectively scheduled.

The first full round of high QA/QC sampling for performance evaluation (baseline sampling) occurred in June 2000 before the injection of any reagent and is known as the biogeochemical characterization. The biogeochemical characterization serves three purposes:

a) confirms or refutes the applicability of the technology to the site

b) establishes the baseline along with historical data

c) provides data necessary for system design

Determination of the baseline conditions of the appropriate biogeochemical parameters is a key element for the design of an ERD system. This evaluation gave a clear indication of the existing conditions and the necessary steps to be taken to optimize the environment to achieve the target reactions.

Dissolved Gas Sampling

ERD processes produce gases that can provide useful information about the process. Additionally, in some cases, the gasses produced may need to be managed for health and safety reasons. The evaluation of the potential for problems with gas generation is generally done as part of engineering design of a system. The depth to the zone of interest, likely paths for vapor migration, proximity of structures and other receptors and potential volumes of gasses produced are assessed in this context. For this demonstration program, it was determined that there were no causes for concern about gas generation hazards or nuisances at Hanscom AFB since no structures lay over the demonstration zone.

As previously described (ARCADIS, 2000; Suthersan, 2002), dissolved hydrogen was monitored in groundwater from IRZ monitoring wells at Hanscom AFB since its concentration can suggest which microbially-mediated redox processes are predominating in the reactive zone. Standard low-flow sampling techniques are used as the basis for sampling groundwater for dissolved hydrogen analysis as hydrogen is an extremely volatile gas that can easily be lost to the atmosphere if exposed to air particularly under turbulent conditions. The use of a flow-through cell increases the protection of samples/measurements against atmospheric loss or contamination. As such, Chapelle, et al. (1997) describe a gas stripping method (also known as the “bubble strip” method) for dissolved hydrogen sampling of groundwater monitoring wells which has become the accepted method given its relative simplicity and short sampling time. Simply stated, the gas stripping method involves creating equilibrium between the dissolved hydrogen in pumped groundwater (employing low-flow sampling techniques) and a small bubble of either air or nitrogen in a flow-through cell. Since hydrogen gas is extremely volatile, an equilibrium condition is reached fairly quickly. After equilibrium between the liquid and gas phases has been reached, a small amount of the gas phase is withdrawn and analyzed using a hydrogen detector (a typical GC technique which in most cases will be conducted by a subcontract analytical laboratory). The gas stripping sampling method and associated analysis (Wiedemeier, et al., 1996) has been incorporated by analytical laboratories performing dissolved hydrogen analysis (in this case Vaportech). They have developed relatively straightforward sampling kits and instructions which draw heavily on the gas stripping sampling method, and were employed here. These gas stripping methods incorporate the following steps:

1. Connect outlet tube from sampling pump to inlet tube of the pre-assembled sampling cell provided by the analytical laboratory.
2. Operate pump to flow at a rate of 100 to 700 ml/min (following laboratory’s recommendation), purge any gas bubbles from sampling cell assembly.
3. Using a syringe (provided in kit), inject 20 to 30 ml (again following laboratory’s recommendation) of air into the cell assembly.

4. Continue to pump through groundwater for a predetermined time between 10 and 30 minutes (depending on laboratory's recommendations which sometimes are dependent on pumping rate).
5. Via syringe, withdraw 1-2 ml of the gas bubble to purge, then withdraw a gas sample (typically 15-20 ml) and re-inject into a laboratory-provided sample vial, which is then shipped back to the analytical laboratory for analysis.

Other essential dissolved gas parameters monitored during the demonstration included light hydrocarbons, namely methane (suggesting methanogenesis), ethane, and ethene (which are by-products/end-products of biological-mediated chlorinated hydrocarbon degradation). These samples were collected in glass bottles provided by the analytical laboratory performing the analysis using low-flow methods. Two (2) 40 mL glass VOA vials with Teflon-faced septa and screw caps were filled for each sample. After collection, liquid samples were cooled and maintained at about 4°C until analyzed. Analytical methods for these light hydrocarbon gasses typically rely on GC techniques similar to those reported by Kampbell, et al., (1989), using SW3810 Modified, which is a static headspace technique for extracting volatile organic compounds from samples. Analytical methods for the light hydrocarbon gasses and CO_2 typically rely on GC techniques similar to those reported by Kampbell et al., (1989), using SW3810 Modified, which is a static headspace technique for extracting volatile organic compounds from samples. Such methods are discussed further in subsequent report sections.

3.5.7.1.3 Saturated Soil Sampling

Soil samples were collected during well installation from within the saturated portion of the aquifer that was targeted for treatment. Samples were collected by driving a split spoon into the formation using a 140-pound weight. Because extensive lithologic information was available based on existing drilling logs, no soil samples were collected above the target depth, and borings were logged based on recovered cuttings. For each of the five new wells (one injection and four monitoring) initially installed, a soil sample from the suspected contaminated saturated zone was sampled and analyzed for the soil parameter list. One field blank and one field duplicate were also analyzed. Data collected was used to supplement existing geologic data and enhance the understanding of contaminant distribution, native soil TOC concentrations, and soil-groundwater contaminant partitioning.

3.5.7.1.4 Sample Shipment and Labeling

All sample sets were accompanied by a chain-of-custody form. Prior to shipment or transfer of custody, all samples were maintained in the custody of the field manager. Upon transfer of custody, the field manager verified the information on each sample label and assured that each container was intact and sealed using custody tape. He/she then signed and dated the chain-of-custody form. The individuals receiving the samples also signed, dated, and noted the time that they received the samples on the chain-of-custody form. This form documents transfer of custody of samples from the field investigator to another person, to the laboratories, or to other organizational elements.

Samples were properly packaged for shipment and delivered or shipped to the designated laboratory for analyses. Because common carriers (Federal Express, Airborne Express, etc.) will not sign chain-of-custody records, the original chain-of-custody form and one copy of the form was placed in a plastic bag inside the secured shipping container when samples were shipped. One copy of the record was retained by the task field manager.

Shipping containers were secured shut using nylon strapping tape and custody seals. A custody seal was placed over the lid of the sample cooler to indicate whether the cooler had been opened during shipment prior to receipt by the laboratory. The original chain-of-custody form was transmitted to the project manager after samples were accepted by the laboratory. This copy then became a part of the project file.

A sample identification system was used to enable the field personnel to establish unique and appropriate identifications for each sample collected. This system incorporated identifiers for the site, sample matrix, the sample location, and the sample number. Field duplicates were designated by the sample code DUP, while equipment, field, and trip blanks were designated with the sample matrix codes EB, FB, and TB, respectively.

The site identification code for Hanscom was HAN. The matrix codes included:

- SS – Soil
- GW – Groundwater
- SG – Shipped ground water sample for hydrogen analysis

Location codes were assigned in the field. Sample numbers were assigned in the field. Thus, for example, a groundwater sample at Hanscom might have been coded: HAN-GW-MW7-1. A duplicate of that sample would then have been coded: HAN-GW-MW7-DUP1. A trip blank for groundwater would be coded: HAN-GW-TB-1.

3.5.7.2 Sample Analysis

ESTCP demonstration sites are subjected to rigorous performance monitoring. Performance monitoring (to assess technology efficacy) for this demonstration was conducted using high quality assurance, low-flow groundwater sampling techniques and analysis during three full sampling rounds and five abbreviated sampling rounds. Analytical parameters, methods and analysis locations/organizations are specified in Table 3-7. Furthermore, records were kept of the color, odor and other readily apparent characteristics of the sampled groundwater. Additionally, some groundwater samples at Hanscom were analyzed on-site by the Base’s GC (operated by an independent contractor). The SOP for this procedure is given in Appendix A-3.

The results of routine process monitoring were used to modify injection protocols and make other process control decisions, in an effort to maintain reducing conditions while avoiding overly depressing pH. Process monitoring was conducted using portable field instrumentation (e.g., Horiba U-22) and varies from relatively low QA (e.g., using down-the-well sondes) to relatively high QA (e.g., using flow-through cells) to measure DO, pH, ORP, specific conductance, and temperature. In addition, field test kits are used to analyze for hydrogen sulfide and ferrous iron, and samples are periodically submitted for laboratory analysis of bromide and TOC. Thirteen process-monitoring events were conducted at Hanscom. Table 3-6 is a week-by-week summary of the demonstration including injections and sampling events. The only groundwater sampling rounds not listed in this table are the initial full sampling round conducted in June 2000 and a “rebound” monitoring round planned for November 2003.

Finally, one soil sample per installed well was analyzed for the parameters listed in Table 3-8, which also summarizes the laboratory used, sample size, preservation, holding time, etc.

Further details of these methods are contained in the final demonstration plan.

3.5.7.3 Experimental Controls

Experimental controls included the use of background well B239-MW and other wells outside of the treatment zone in the groundwater monitoring program. Results for these control samples are discussed in Sections 4.3.3.3.4, 4.3.3.3.5, and Appendix A-6a.

3.5.7.4 Data Quality Parameters

Representativeness, completeness, comparability, accuracy and precision of the demonstration data are addressed in the data validation memoranda in Appendix A-6b. Deviations from the QA sampling plan, problems associated with QA samples, and their resolutions are recorded in Appendix A-6c. Relatively few data quality problems were identified, and most of these were judged inconsequential or were resolved by re-sampling or relying on alternate measurements of the same parameter.

CAH data in general were shown to be very reliable. Most of the data quality problems encountered during various sampling rounds occurred with the field data or the TOC/DOC data. In particular, the high levels of organic carbon in the injection wells caused problems with field measurements. However, these parameters are used more for process operation and interpretation than to assess the effectiveness of the technology. Therefore, it was judged that these problems did not materially affect the overall demonstration results.

3.5.7.5 Data Quality Indicators

Validation of the demonstration data were performed using the QA/QC criteria set forth in the “USEPA Contract laboratory (CLP) National Functional Guidelines for Organic Data Review,” revised in June 2001. The data validation memoranda in Appendix A-6b describe the methods used to calculate data quality, and their results.

3.5.7.6 Calibration Procedures, Quality Control Checks, and Corrective Action

Calibrations of laboratory analytical equipment are addressed by the data validation memoranda in Appendix A-6b, which also describe the use of blanks, surrogates, matrix spikes and laboratory control spikes.

Procedures used to calibrate field equipment are described in the project’s demonstration plan (ARCADIS, 2000). Specific instances of known problems with field equipment or measurements, and their resolutions, are recorded in Appendix A-6c. Relatively few problems were encountered, and many of these were able to be resolved by re-sampling or relying on alternate measurements of the same parameter.

3.5.8 Demobilization

Following the final injection event, reagent solution mixing and injection equipment was rinsed with potable water to remove residual molasses. No other above ground equipment or facilities were used during this demonstration, so no further demobilization was required. Underground equipment utilized during this demonstration was limited to the injection well and monitoring wells which were installed for this demonstration. At the request of the Air Force, these wells were left in place for use in the future for monitoring of the Site 1 pump and treat system. A written confirmation of the Base's wish to retain the wells is included in Appendix A-4.

3.6 Selection of Analytical/Testing Methods

Analytical methods used in the demonstration are listed in Table 3-7. Field instruments used in the program were identified in ARCADIS SOPs, in the project demonstration plan (ARCADIS, March 2000).

3.7 Selection of Analytical/Testing Laboratory

The locations or laboratories where analyses were performed are indicated in Tables 3-7 and 3-8. The majority of analyses were performed either by ARCADIS in the field or at Severn Trent Laboratories (STL) in Tampa, Florida (Mass DEP Certificate #M-FL224), or Savannah, Georgia (Mass DEP Certificate #M-GA006). Specialized analyses for dissolved gases in groundwater were performed by Vaportech Services, Inc. of Valencia, Pennsylvania.

In addition, although it was not planned in the demonstration plan, numerous additional rounds of TCE and DCE analyses by GC were provided courtesy of Tom Best of Hanscom AFB. These included samples collected on some occasions by the Base's contractor (Shaw/IT) and on other occasions by ARCADIS. The analyses were performed at Hanscom by IT. As discussed in Section 4.3 the data sets with and without the on-site data led to virtually identical conclusions, suggesting that the two laboratories are in rough agreement.

Grain size testing of soil samples was performed by Engineering Consulting Services, Inc. of Research Triangle Park, North Carolina.

4. Performance Assessment

4.1 Performance Criteria

Performance criteria are listed in Table 4-1. Criteria were based primarily on performance objectives agreed upon by ESTCP/AFCEE and ARCADIS in the planning stages of the project (see demonstration plan, ARCADIS, March 2000). Other criteria are included in an effort to conform with new reporting guidance issued during the preparation of this report (ESTCP, October 2002).

4.2 Performance Confirmation Methods

Performance confirmation methods and brief summaries of results are listed in Table 4-2. Because of the complexity of the demonstration (including the nature of the geology and the biology of CAH biodegradation), results are not easily presented in a table. Moreover, the temporal and spatial relationships of the multiple lines of evidence cannot be fully conveyed in this summary table. Therefore, references to relevant text are included as needed. A comparison of demonstration results with objectives is given in Section 4.3.7.

Data collection methods and data analysis procedures used in this demonstration, including the Quality Assurance Project Plan, were established in the project demonstration plan (ARCADIS G&M, March 2000). (See especially, Section 3.2, Pre-Demonstration Sampling and Analysis; Section 5.4, Sampling Plan; and Section 9.0, Quality Assurance Plan.)

4.3 Data Analysis, Interpretation and Evaluation

4.3.1 Performance Overview

The demonstration-scale system at Hanscom AFB was operated for two years between October 2000 and October 2002. During that time, the data discussed below demonstrated highly effective, complete TCE removal in a source area that had a long history of fairly stable TCE concentrations before treatment. Evidence of complete treatment – a buildup of ethene, reduction in *cis*-1,2-DCE and no accumulation of VC was also seen in the most effectively treated downgradient wells. Effective treatment was seen only where substantial substrate (molasses and its breakdown products) was observed in downgradient monitoring wells. The layout of the injection and monitoring well system was designed for southeasterly groundwater flow. During the demonstration period, the predominant direction of flow was eastward. Thus, it is suspected that a larger IRZ was formed than what was observed, but that the monitoring well network was not positioned to completely delineate it.

4.3.2 Process Monitoring Results and System Operational Adjustments

4.3.2.1 Injection Rates and Field Parameter Observations

Injections of aqueous molasses solution that were begun in October 2000 (see Table 3-6 for a detailed list) were successful in quickly achieving favorable reducing conditions in the lower aquifer, as evidenced by depressed DO and ORP measurements in nearly all downgradient wells after a short period of time (Figures 4-1 and 4-2). Figure 4-3 shows that TOC in the injection well (typically measured immediately prior to the next injection event) remained steady in the desired range from October to May 2001. The pH of the injection well had also markedly decreased (Figure 4-4) which limited the rate of injection. See Sections 1.3.2, 4.1.2.1, 4.5, 5.3 and 6.2 of the protocol (Suthersan, 2002) for a detailed discussion of the causes of pH drop in EARP systems and its management. In brief, the pH of groundwater generally decreases during the injection of degradable organic substrates. The magnitude of the pH decrease depends on the dose of substrate and the natural buffering capacity of the system (both the groundwater and the aquifer solids). This site exhibited relatively low buffering capacity, and pH was controlled by careful carbon dose control and injection of a clean water “push” following reagent injection to disperse the dose away from the immediate vicinity of the well. As shown in Figure 3-15, the injection rate during this initial period (October 2000 – February 2001) was approximately 80 lbs of substrate per week. Thus the delivery of reagent (as indicated by only slightly elevated TOC and Bromide) to downgradient wells was inadequate after 2-3 months of such an injection regimen.

Thus, the injection frequency was increased to roughly a biweekly schedule and each molasses injection was followed by a water push (an injection of just water without diluted molasses) beginning February 2001. This revised dosing regime (averaging around 150 lbs/week as shown in Figure 3-15) greatly improved the distribution of reagent in roughly five weeks, delivering TOC and DOC to monitoring wells RAP1-6T (installed in the lower aquifer) and IRZ-1 starting in late March 2001 (Figures 4-5 and 4-6). As discussed in Section 4.3.4.2, a variety of methods were used to estimate velocity at this site, which suggested groundwater travel times on the order of 40 to 50 days to the initial transect of monitoring wells.

The reactive zone continued to be monitored and beginning in September 2001, the reagent dosage was doubled for most events, while still keeping a bi-weekly injection frequency and water push, in order to expand the size of the reactive zone and in response to increased groundwater flow (as shown in Figures 4-7 and 4-8, gradients increased in early summer 2001 and stayed relatively high throughout the demonstration) and slightly increased DO. As shown in Figure 3-15 the injection rate during this period (September 2001 through February 2002) was in the range of 150-250 lbs/week. It is important to note that despite the increased injection rate during this period the TOC at the most impacted pair of downgradient monitoring wells dipped (Figure 4-5). The reasons this occurred is discussed in Section 4.3.4.

The injection rate was reduced somewhat between March and September 2002 in response to diminished pH (frequently in the range of 3.9-4.0). As shown in Figure 3-15 the injection rate during this period was in the range of 100-200 lbs/week. However, the observed TOC in monitoring wells RAP1-6T and IRZ-1 (Figure 4-5) remained fairly high during this period.

Observations made between September 16 and 18, 2002, showed high DO in the monitoring wells (Figure 4-1) and TOC toward the low end of the desirable range (Figure 4-3). Moreover, as discussed in Section 4.3.4 potentiometric surfaces (Figures 4-23 through 4-26) indicated that the system was just recovering to a normal flow pattern following a series of outages in the pump and treat system that had likely altered the flow direction. Therefore the substrate injection rate was increased for a month to its highest level during the demonstration (Figure 3-15) in order to quickly restore the system to normal conditions.

At this site a fairly regular injection frequency has proven to be effective given its relatively porous geology and relatively high groundwater velocities, though injection well pH was monitored before each injection to determine if an injection could be done without excessive pH drop. The pH in the injection well held fairly steady between 3.9 and 5.5, near the low end of the acceptable range. However, the pH in all of the monitoring wells was basically unaffected by injection events typically holding between 6.0 and 7.5, regardless of whether they received significant substrate as indicated by TOC.

4.3.2.2 Changes in Groundwater Flow

Seasonal variations in the direction and magnitude of the groundwater gradient were observed (see Figures 3-8 and 4-9 through 4-27 for potentiometric surfaces as well as gradient plots in Figures 4-7 and 4-8). These appear to be caused at least in part by operational problems with the Base's pump and treat system (Figure 4-28) and variations in precipitation (see Figure 4-29).

These variations in magnitude and direction of gradient appear to have changed the size and shape of the reactive zone markedly. As shown in Figures 4-5 and 4-6, there were two periods where fairly strong doses of reagent were delivered to wells IRZ-1 and RAP1-6T, from late March 2001 through July 2001 and again from March 2002 through September 2002. These variations in hydrogeology and reactive zone shape are discussed more completely in Section 4.3.4.

4.3.2.3 TOC, DOC, and Other Measures of Reactive Zone Influence

In addition to TOC and DOC, several other measures can be used as indicators of reagent delivery and the consequent creation of the reactive zone: concentration of the bromide tracer, specific conductance and visual and visual/olfactory observations of groundwater. Bromide tracer shows a pattern essentially similar to that of TOC (primarily substrate), suggesting that the TOC was not significantly more sorbed to the soil matrix than the "nonreactive" bromide tracer at this site. As discussed above, the soil TOC is low at this site so this observation is reasonable. Specific conductance in IRZ-1 and RAP1-6T also shows two peak periods from March 2001 through early fall 2001 and again from later March 2002 through fall 2002. It is interesting to note that the peak in the conductance plot is less sustained for RAP1-6T than for IRZ-1 in both cases. This suggests that RAP1-6T was toward the fringe of the reactive zone formed. A similar trend is seen in the TOC/DOC data although the data points were less frequently obtained for those parameters.

Visual and olfactory observations were recorded periodically when groundwater samples were extracted from monitoring wells. Color, odor, turbidity, and other qualitative observations about the samples were documented. These observations were standardized during data entry into numbers rating the observed level of reagent impact implied by the sample characteristics in an effort to present the qualitative data graphically. The numeric rating system utilized a scale from 0 to 5, with 0 (actually 0.1 so that the measurement would show up graphically) corresponding to no impact whatsoever and 5 corresponding to undiluted molasses injection solution. The numerical ratings were as follows:

0.1	No Influence	No color, odor, turbidity or other qualitative observations to suggest an impact
1	Slight Influence	One of the following: slight color, slight odor, or turbidity
2	Significant Influence	Two or more of the following: slight color, slight odor, or turbidity
3	High Influence	One or more of the following: moderate-to-strong color, odor, and/or turbidity
4	Very High Influence	Strong color and odor
5	Molasses Solution	Theoretical maximum. Of course, there will always be some dilution; thus this rating was never assigned to a sample.

Although not exactly in agreement this data set also suggests peaks in spring and summer 2001 and 2002 for reagent impact at IRZ-1 and RAP1-6T.

It is noted that the measured TOC values were not always higher than corresponding DOC values. Evaluations of field and laboratory data were undertaken in an attempt to explain this discrepancy (see Appendix A-6c). However, no universal explanation was found. Since these data were used only as process monitoring parameters, the discrepancy is not considered critical.

4.3.2.4 Bromide Tracer Data

The bromide tracer data (Figure 4-55 and Table 4-3) shows that:

- Bromide was undetected in all wells except the upper aquifer well in the background monitoring round
- Bromide was undetected in 9 straight monitoring rounds in the upgradient well B239
- High concentrations of bromide were detected only in RAP1-6T and IRZ-1 and generally coincide with other indicators of reactive zone influence such as TOC, DOC, BOD and COD (Figures 4-5, 4-6 and Table 4-4).
- Other than a brief period between late March 2001 and mid July 2001 all of the collected bromide data show that the injected fluid constituted less than 2% of the water sampled at the monitoring wells.
- Bromide concentrations increase gradually with time after the first two sampling rounds done on well IRZ-5 (recall that this well was installed after the demonstration began to better define the northeast edge of the reactive zone). TOC and DOC show a similar trend (Figures 4-5 and 4-6) suggesting that this well was receiving some influence at the far downgradient edge of the reactive zone by the end of the demonstration.

- Wells IRZ-2, IRZ-3, and IRZ-4 show erratic, low but often-detectable bromide concentrations. This when coupled with similar DOC, visual and olfactory data (Figures 4-6 and 4-45) may suggest that these wells were on the far fringes of the reactive zone and thus may have received occasional very dilute influences from the injection well.
- RAP1-6S in the upper aquifer begins to receive trace bromide starting in November 2001. This suggests some leakage or mixing into the upper aquifer and will be discussed more in Section 4.3.6.1.
- RAP1-6R in the bedrock aquifer was the only well to have detectable bromide before injection (perhaps due to differences in geochemistry). This well has no clear trend in bromide concentration during the demonstration.

4.3.3 CAH Treatment

CAH data for the three full groundwater monitoring rounds are summarized in Tables 4-5, 4-6, and 4-7.

4.3.3.1 Summary of CAH Treatment Results

Our discussion of CAH treatment will focus primarily on the two monitoring wells that received substantial doses of substrate TOC - RAP 1-6T and IRZ-1 (Figure 4-5) - and secondarily on the injection well. These two monitoring wells were also the only ones in the lower aquifer where substantially increased levels of methane were observed (Figure 4-30). Although reducing conditions as evidenced by reduced DO and ORP were observed at other wells, we would not expect from our theoretical understanding to observe treatment in the absence of delivered substrate (Suthersan, 2002).

The best treatment results were observed at IRZ-1 (approximately 45 feet downgradient) (Figure 4-31). At this well highly effective treatment of TCE was observed beginning in March 2001, 5 months after injections began and shortly after single injections with water pushes began (>95%reduction vs. pretest concentrations). Substantial treatment of *cis*-1,2-DCE (eventually >85% reduction in pretest concentration) was not observed until March 2002, a year later, during a second period of high TOC delivery. By March 2002, complete degradation was evidenced by the substantial increase in ethene production (Figure 4-32). The rate of ethene production continued to climb through the end of the demonstration in October 2002, indicating that treatment effectiveness continued to increase after two years of system operation. Ethene concentrations at this well increased to more than 20 times the pretest value.

The layout for the demonstration was designed to be centered around monitoring well RAP1-6T (approximately 40 feet downgradient), which had 14.5 years of relatively stable TCE, DCE and VC results before the demonstration began (Figure 4-33). A sharp decline in TCE was observed within 6 months of the beginning of injection, coinciding or slightly preceding the appearance of substrate as measured by increased TOC and conductance (Figure 4-34). TCE levels for seven straight monitoring rounds (between 3/26/01 and 9/7/01) were at 10% or less of the average of the proceeding 10 years (Figure 4-35). Then, for reasons discussed in detail below, the IRZ shifted away from this well as evidenced by the significant decline in TOC concentrations at this well. As a result of this shift, TCE, DCE and VC concentrations rebounded. These concentrations dipped again when substrate levels increased, although it appears that the typical groundwater flow direction was somewhat more easterly rather than northeasterly as planned. Thus this well was probably at the fringe of the effective reactive zone for much of the demonstration period.

Due to fluctuations in the groundwater flow direction, rebounds were observed at IRZ-1 and RAP1-6T in the fall and winter of 2002. Concentrations declined again after substrate was restored in spring of 2002.

Although it is by definition a less accurate measure of the overall effectiveness of the reactive zone, it is useful to note that substantial evidence of effective treatment of all chlorinated species was seen at the injection well, even in data corrected for the dilution effect of the injected solution. Concentrations of TCE and VC were reduced by more than 95% for TCE and 85% for VC over a long period from May 2001 through the end of the demonstration in October 2002. DCE decreased substantially less (at most about 75%). This suggests that although CAHs were being completely degraded, desorption from a localized source area continued (Figure 4-36). This difference in temporal trends among the CAH constituents confirms that a degradation effect (and not merely dilution) is present.

The wells that did not get substantial, consistent doses of substrate showed no evidence of treatment or at most modest decreases in TCE only (IRZ-2, IRZ-3, IRZ-4 and IRZ-5 in the targeted lower aquifer, RAP1-6R in the bedrock aquifer and RAP1-6S in the upper aquifer). This strengthens the conclusions that substrate availability is linked with improved biodegradation and that contaminant removal was due to enhanced biodegradation rather than displacement.

4.3.3.2 Methodologies Used in CAH Data Analysis

We used several different approaches to understand the CAH data set from this demonstration. We had available CAH data from three primary sources:

a) sampling conducted by ARCADIS using high QA/QC methods with off-site GC-MS analysis by STL (1 round pre-demonstration and 7 rounds during the demonstration)

b) sampling conducted before and during the demonstration by ARCADIS or the Base’s contractor (IT) with analysis conducted using an on-site GC by IT (as many as 12 additional rounds during the demonstration with many more prior to the demonstration)

c) periodic compliance monitoring of some wells conducted before and during the demonstration by the Base’s contractors using various off-site laboratories (15 or more rounds).

Between all these sources some of the wells had a wealth of data – as much as 65 samples over 16 years for RAP1-6T (of which 26 were during the treatment period)!

Various approaches were used to graphically review and interpret the data:

a) plots of CAH concentration vs. time, with indications of the injection times

b) plots of CAH concentration corrected for dilution as measured by the observed concentration of bromide tracer

c) bar-line plots of CAH concentration compared to the concentration of indicators of substrate delivery such as TOC or conductance

d) plots of CAH concentration on a molar rather than mass/volume basis

e) plots of an “MCL index” (Payne, 2002) designed to measure overall progress toward reduced risk from CAHs. Note that this index should not be construed to imply that risks from CAHs are necessarily additive.

The significance of changes in concentration was determined primarily by comparisons to pretest concentrations, or in some cases, in comparisons to a level baseline that was observed before and for a period after injection before biodegradation evidently began. Although one well upgradient of the injection well (B239) was routinely sampled, it didn’t turn out to be suitable for upgradient and downgradient concentrations for several reasons:

a) pretest data and modeling by a previous consultant strongly suggested that the demonstration zone was in a source area

b) concentrations at this well were relatively low and erratic for several years prior to and during the demonstration

c) B239 is proximate to extraction well #6 which may exert a localized influence on it

It was judged impractical to install an additional upgradient well between IRZ-INJ and B239 because of the intervening active runway.

In most cases sufficient data was available that the presence or absence of trends in pre- and post- treatment concentrations could be readily discerned by inspection. In key cases, the students t-test was used to verify these conclusions. Multiple lines of evidence were also sought to confirm that biodegradation was being enhanced (NAS, 2000):

a) evidence that biogeochemical conditions were appropriate for anaerobic biodegradation was obtained and reviewed

b) the trends and time sequence of product production (i.e., DCE, VC, and ethene) were sought to verify that observed decreases in target compounds were not due to dilution and fit with the current theoretical/laboratory understanding of CAH biodegradation

c) trends in historical data were compared inside and outside of the reactive zone

d) tracer (bromide) corrections were used to verify that dilution was not the primary cause of observed trends

e) downgradient and side-gradient well data were reviewed to rule out displacement effects

More details about particular methods of data interpretation are provided in the sections that follow.

4.3.3.2.1 Dilution Calculations Using Tracer

We have assumed that bromide tracer used is indeed conservative and does flow along with and at the same rate as the injected liquids. Thus the amount of dilution in a given well should be directly proportional to the amount of bromide that shows up in that well. For clarification, as an extreme example, if 100 mg/L of bromide were injected into the injection well and then 100 mg/L bromide were withdrawn a week later at a monitoring well located one-week downgradient of the injection well, we would surmise that the monitoring well contains only injection fluid. Likewise, if 0 mg/L bromide were measured in the monitoring well, none of the water from the injection well has made it to the monitoring well and there is thus no dilution.

Based on this logic, VOC measurements were corrected by calculating a dilution factor per the following equation:

$$DF = 1 - \frac{[Br]_{MW}}{[Br]_{Inj}}$$

Where,

DF = dilution factor (that is, the percentage of monitoring well sample that is not dilution water),

$[Br]_{MW}$ = the bromide concentration measured on a sample taken from a monitoring well on a given date, and

$[Br]_{Inj}$ = Injection fluid bromide concentration (an approximate running average of injection fluid bromide concentrations made around the assumed travel time of the injection well to the monitoring well). This takes into account both the molasses solution and the water "push" fluids.

Then, the VOC concentration for a given monitoring well sample was corrected by calculating its actual concentration per the following equation:

$$VOC_{actual} = \frac{VOC_{measured}}{DF}$$

As an example, consider the Br concentration measured on a sample from RAP1-6T on 4/6/01. The measured Br in RAP1-6T was 21.4 mg/L, and the average injection concentration was determined to be 60 mg/L. Thus the dilution factor was: 1 - 21.4/60 = 0.643. The TCE concentration from this sample was measured to be 5.0 mg/L. Therefore, the actual, undiluted concentration should be 4.8 / 0.643 = 7.8 mg/L.

4.3.3.2.2 Bar-Line Plots of Substrate Dose vs. CAH concentration

We have prepared bar-line plots (Figures 4-31 and 4-34) to graphically show how the substrate dose (as measured by TOC and specific conductance and shown by the bars) affects the key VOCs (TCE and DCE shown by the lines).

4.3.3.2.3 MCL Index

The MCL index was developed to represent the cumulative effect of MCL exceedances for multiple compounds. Over a series of monitoring events, the index provides a sense of the overall progress of remediation relative to groundwater remediation goals (if based on MCLs) or drinking water toxicity (the basis for MCLs).

The index normalizes concentrations of all constituents to show the cumulative effect of exceedances of MCLs for multiple compounds. For instance:

$$\text{MCL Index} = \frac{PCE}{MCL_{PCE}} + \frac{TCE}{MCL_{TCE}} + \frac{cisDCE}{MCL_{cisDCE}} + \frac{VC}{MCL_{VC}}$$

For the Hanscom AFB site, only the primary detected CAHs were included in MCL Index calculations. Note that the use of this index should not be taken to imply that the risk from these compounds is necessarily additive.

4.3.3.2.4 Rate Calculations

The methodology for the rate calculations is discussed in Section 4.3.3.5.

4.3.3.3 Detailed Discussion of Observations at Individual Wells

4.3.3.3.1 CAH Data at Well IRZ-1

All of the available CAH data for this key well is plotted on a concentration basis in Figure 4-37. The initial concentrations of TCE, DCE and VC are reasonably consistent with those in neighboring wells measured in the same sampling round (Figure 3-14). Those neighboring wells include RAP1-6T, which has a long history of concentration stability. Thus although only one pretest round was available at IRZ-1, we can be reasonably certain that this range of CAH concentrations is representative.

TCE concentrations in IRZ-1 are erratic for the first several months after injection begins, swinging both substantially above and below the baseline. This may represent an interplay between not fully established enhanced biodegradation processes and enhanced desorption processes (see Section 4.3.1 of Suthersan, 2002 for a discussion of desorption effects in ERD systems). Then four sampling rounds from March 26, 2001 to July 11, 2001 showed dramatically lower TCE concentrations. These rounds included both on-site and off-site analyses. Essentially the same trend is shown in the high QA/QC offsite laboratory only data set (Figure 4-38) and in the dilution-corrected plot (Figure 4-39). As discussed previously, the bar-line plot (Figure 4-31) shows that this dip coincided with an increase in the presence of substrate, as indicated by TOC and specific conductance. During this March to July 2001 period DCE is stable, VC may be slowly declining (Figure 4-37), and methane (Figure 4-31) and ethene (Figure 4-32) are low and only a trace of hydrogen sulfide was observed (Figure 4-40). DO (Figure 4-1) and ORP (Figure 4-2) had substantially declined. These data taken together suggest enhanced degradation is occurring, but thermodynamically favorable electron acceptors have not been consumed to allow complete degradation to ethene.

Sometime between July and October 2001 the concentration of substrate at IRZ-1 as indicated by TOC and specific conductance dipped markedly which resulted in a rebound in the concentrations of most CAH analytes, especially TCE (see Figures 4-3, 4-31, and 4-37). This appears to have been due to changes in flow conditions, since the injection rate of substrate remained the same or even increased.

TOC and specific conductance began to increase, and TCE and VC decreased again between February and October 2002 (Figure 4-37). However, unlike the earlier period of high substrate concentration during this period, *cis*-1,2-DCE dramatically decreased! Concentrations of this analyte had been between 2600 and 4600 µg/L in 17 straight analyses between June 2000 and January 2002 were less than 1,000 µg/L in four of five monitoring rounds between February and October 2002. Ethene concentrations (regarded as the best indicator of complete CAH biodegradation) had not increased substantially by November 2001, but increased significantly by the March and October 2002 monitoring rounds (Figure 4-32). Ethene concentrations at IRZ-1 eventually increased to more than 20 times the pretest value. Methane concentrations that had begun to increase noticeably in November 2001 remained steady through the later portion of the test at a concentration of about 2 mg/L. Dissolved oxygen was typically less than 1 mg/L and ORP was typically between –150 mV and –200 mV during that period. As shown in Tables 4-5, 4-6, and 4-7, sulfate levels had substantially diminished in this well by May 2001 and were also low in October 2002. With the detection of trace sulfide, this suggests the conditions were at least in part, sulfate reducing. Although this is slightly above the range (below –240 mV) typically quoted for methanogenesis (Morin and Henry, 1998) the measurement of ORP is notoriously inaccurate in groundwater systems due to lack of equilibrium among other causes (Lindberg and Runnells, 1984). Another possible interpretation is that the methane was generated and the CAHs degraded somewhere upgradient of IRZ-1 where the ORP is lower. Thus, multiple lines of evidence suggest that complete degradation of CAHs was achieved upgradient of IRZ-1 under sulfate reducing/methanogenic conditions.

Analysis of the dataset using the off-site laboratory data only (Figure 4-38) and the dilution corrected data (Figure 4-39) supports the same conclusions.

4.3.3.3.2 CAH Data at Well RAP1-6T

The RAP1-6 cluster was the only preexisting well in the immediate demonstration area. Conductance (Figure 4-41), TOC (Figure 4-5) and DOC (Figure 4-6) all suggest that the periods of elevated substrate concentration at this well were less sustained than at IRZ-1. As discussed more completely in Section 4.3.4, it appears that the typical groundwater flow direction was somewhat more easterly rather than southeasterly as planned. Thus this well was probably at the fringe of the effective reactive zone for much of the demonstration period. As shown in Figure 4-33, TCE and VC concentrations in monitoring well RAP1-6T immediately before the demonstration started in 2000 were essentially unchanged from the first measured values in 1986. Although a pump and treat system at the site had been operated for much of that time and other remedial measures were implemented which dramatically reduced concentrations in other areas of the site, they had little effect at RAP1-6T (see Figure 4-33, see also Hanscom AFB, 2002). The data shown on Figure 4-33 suggests that 1,2-DCE measured prior to 1998 is primarily *cis*-1,2-DCE. Based on this there is no clear trend in the DCE data except that it generally remained between 3,000 and 6,000 µg/L.

The concentration of TCE and DCE appeared to rise slightly in the fall of 2000 immediately after injection began on October 11th, which could possibly be a desorption effect. However, since the rise was slight and occurred so rapidly the existence of a desorption effect in this instance is questionable.

A sharp decline in TCE and a lesser decline in DCE was observed beginning in mid-November 2000 one month after injection and continued until September 2001, eleven months after the beginning of injection (Figure 4-35). This decline coincided or slightly preceded the appearance of substrate as measured by increased TOC and conductance (Figure 4-34). TCE levels for seven straight monitoring rounds (between 3/26/01 and 9/7/01) were at 10% or less of the average of the proceeding 10 years (Figure 4-35). Since VC was not measured by the on-site GC, there is less data for this compound, however it appeared to have a coincident, but slower decline during a series of four monitoring events from November 2000 to July 2001.

Then, for reasons discussed in detail below beginning in September 2001, substrate delivery to this well decreased markedly which led to a rebound in TCE, DCE and VC concentrations that peaked in November 2001. TCE concentrations dipped again from January to October 2002 in the presence of increased substrate levels although DCE and VC concentrations were too erratic to allow firm conclusions during that period. However, ethene at this well increased gradually and fairly steadily during the demonstration (Figure 4-42), with its most significant increase occurring in 2002. However, ethene never reached the high levels seen at IRZ-1.

The conclusions discussed above about trends in CAH data at this well are unchanged when the data is examined using the smaller off-site laboratory samples (Figure 4-43) or dilution-corrected (Figure 4-44) datasets.

ORP during most of the demonstration period ranged from –50 to –200 mV at this well (vs. 2 mV pretest) and DO was almost continuously held to less than 1 mg/L until October 2002. Modest increases in hydrogen sulfide (Figure 4-40) and decreased sulfate (Tables 4-5, 4-6, and 4-7) were observed in several monitoring rounds beginning in May 2001. Although methane concentrations increased in each monitoring round, increases to levels dramatically above those seen in any well in the background monitoring round did not occur until between November 2001 and March 2002. March 2002 was the peak for methane at this well and it had diminished some by October 2002 (although it was still substantially above background values). Taken together this data suggests that the predominant microbial processes in the vicinity of this well were probably iron reducing or denitrifying until May 2001, sulfate reducing in summer and fall 2001, and did not become methanogenic until the end of 2001, more than a year after injections began. Although very good TCE treatment was achieved at this well, more sustained delivery of substrate would probably be necessary for optimum rates of complete degradation to occur.

4.3.3.3.3 CAH Data at the Injection Well IRZ-INJ

Although it is by definition a less accurate measure of the overall effectiveness of the reactive zone since it is more prone to dilution effects and other artifacts, we discuss here the injection well data because:

- Since sampling was done before rather than immediately after injection events the water sampled from the injection well should represent the groundwater at the upgradient end of the reactive zone, where substrate has mixed at high concentration with the formation water
- Dilution correction using the bromide tracer can help estimate the effects of dilution
- The analysis of this data is similar to the conduct of field push-pull pilot tests which have been widely recommended.

Substantial evidence of effective treatment of all chlorinated species was seen at the injection well, even in data corrected for the dilution effect of the injected solution. Concentrations of TCE and VC were reduced by more than 95% for TCE and 85% for VC over a long period from May 2001 through the end of the demonstration in October 2002. DCE decreased substantially less (at most about 75%). The sequence of observed substantial concentration decreases was TCE first, then VC, followed by DCE. The continued presence of DCE suggests that although CAHs were being completely degraded, desorption from a localized source area continued (Figure 4-36) through the end of the demonstration (since the low concentration at B239 discussed below suggests that upgradient inputs were small).

As shown in Figure 4-3, TOC levels in the injection wells were maintained at a high level fairly consistently throughout most of the demonstration, which is logical since the injection well area is much less subject to variations in flow direction than the downgradient wells. The one major dip in this concentration on July 11/12, 2001 coincided with peaks in the DCE and VC concentration trends (Figure 4-36). Visual and olfactory observations (Figure 4-45) also suggested that this well was surrounded by a consistent reactive zone. However hydrogen sulfide levels were generally only modestly elevated (Figure 4-40), methane concentrations showed no clear trends (Figure 4-46) and ethene levels actually decreased as the demonstration proceeded (Figure 4-47). Data for the very light gasses may be unreliable because this well was described at some times as “frothy” due the effects of substrate. It is also possible that ethene decreased as most of the available CAHs in the immediate area was consumed by biodegradation and rates were limited by mass transfer from a source.

4.3.3.3.4 Upgradient Monitoring Well B239 CAH Data

When the demonstration zone was laid out, this well (which was present before the demonstration) was intended to serve as an upgradient control well since it lies between the primary Site 1 source and the demonstration zone. CAH data from this well is shown in Figures 4-71 through 4-73. Though this well is indeed hydraulically upgradient of the demonstration zone, and it lies just opposite the runway from the injection well, the data shows it has much lower and more erratic levels of CAHs than wells within the demonstration zone. Potentiometric surfaces (i.e., Figures 3-8, 4-11, 4-12) suggest that this well, though downgradient of extraction well BIW-6, may at some times be within that well’s zone of influence and is certainly benefiting from the remediation influence of that well. Data acquired during this demonstration suggest the presence of another CAH source between B239 and RAP1-6T (see Section 3.4). While classified as a lower aquifer well the screen in this well is somewhat shallower than the other lower aquifer wells used in this demonstration (see Figure 3-12). These data taken together suggest that pump and treat has been successful in significantly reducing observed concentrations immediately to the northwest of the runway but has not yet reached MCLs and may have reached an asymptote.

4.3.3.3.5 CAH Data at all Other Monitoring Wells

With only a few exceptions CAH concentrations at the other wells monitored for this demonstration showed no evidence of treatment or at most modest decreases in TCE only (IRZ-2, IRZ-3, IRZ-4 and IRZ-5 in the targeted lower aquifer, RAP1-6R in the bedrock aquifer and RAP1-6S in the upper aquifer). These data have been reported in:

- Figure 4-48 for IRZ-2,
- Figure 4-49 for IRZ-3,
- Figure 4-50 for IRZ-4,
- Figure 4-51 for IRZ-5,
- Figure 4-52 for RAP1-6R in the bedrock aquifer, and
- Figure 4-53 for RAP1-6S in the upper aquifer.

These wells were generally outside of the IRZ. Some exceptions to this are that IRZ-5 appeared to be on the very downgradient edge of the IRZ near the end of the demonstration. Similarly, RAP1-6S shows some influence late in the demonstration. This is discussed in Section 4.3.2.4. The following observations were made for completeness:

- VC in well IRZ-2 which appears to show a consistent although modest downward trend until the last data point in November 2002 when it rebounded to initial conditions
- TCE in IRZ-3 declines about 50% in the spring and summer of 2001, then rebounds in the fall of 2001, and remains fairly steady throughout the remainder of the demonstration period
- Ethene production in IRZ-5 appears to steadily increase after this well was installed, after the demonstration had already begun (Figure 4-47)
- TCE in RAP1-6R declined slowly during the demonstration. However, an examination of the ratio of TCE to DCE (on a concentration basis) both before and after injections begin suggests that a trend that was ongoing was little changed by the demonstration (Figure 4-54).

As seen in the TOC (Figure 4-5), DOC (Figure 4-6), conductance (Figure 4-41), bromide (Figure 4-55) and visual/olfactory observations (Figure 4-45) plots none of these wells had consistent evidence of substantial substrate delivery. However DO and ORP did appear to decrease in many of these wells (Figures 4-1 and 4-2). This strengthens the conclusions that substrate availability is linked with improved biodegradation. Since these wells were above, below, upgradient and side gradient from the wells that showed clear evidence of biodegradation (IRZ-1 and RAP1-6T) this strengthens the conclusion that contaminant removal at those three wells was due to enhanced biodegradation rather than displacement or dilution.

4.3.3.3.6 MCL Index

The MCL index calculation (Figures 4-56 through 4-59) of course mirrors the VOC concentration plots – showing risk reductions were achieved for TCE in all wells and for DCE in IRZ-1 and IRZ-INJ. But they emphasize the importance of VC. Although VC did not increase during the demonstration and actually decreased somewhat at IRZ-1 and substantially IRZ-INJ it is typically the last of the chlorinated ethenes to degrade under anaerobic conditions. It is also important to note that VC is the most readily degraded under aerobic conditions of the chlorinated ethenes so would be expected to degrade outside the reactive zone.

4.3.3.3.7 Statistical Analysis of CAH Data

A one-sided Student’s t-test was conducted to compare concentrations of CAHs before the demonstration to those during the demonstration. The t distribution is assumed to be normal, and the variances of the two samples are assumed not to differ significantly. Using data for RAP1-6T, all available data before October 11, 2000 were compared to all data collected after October 11, 2000. For IRZ-1, post-demonstration data starting in late 2001 through October 2002 were used instead of all post-October 2001 data, to reflect the daughter product response to methanogenic conditions. Where multiple analyses were conducted on one sample on the same day (e.g., when both on-site and traditional laboratory testing were conducted on the sample), results were averaged for a single data point.

Statistics for each data set were as follows:

Well	CAH	Data Set	Mean Conc. (μg/L)	Std. Dev.	Sample Size	T	Probability
RAP1-6T	TCE	Before	1289	615	24	4.75	1.2E-05
	TCE	After	444	528	19		
	Cis-DCE	Before	3763	1363	24	1.45	0.0769
	Cis-DCE	After	3230	937	19		
	VC	Before	955	373	14	1.92	0.0346
	VC	After	679	272	9		
IRZ-1	TCE	Before	492	646	2	0.89	0.2049
	TCE	After	238	252	6		
	Cis-DCE	Before	3219	54	2	1.11	0.1540
	Cis-DCE	After	1922	1562	6		
	VC	Before	1100	---	1	0.72	0.2732
	VC	After	831	323	3		

The last column indicates the maximum probability that the observed change in concentration was due to random variation. We note that a simple t-test is probably not the best statistical approach to this problem, because the conditions that impact treatment efficiency (i.e., groundwater flow direction and thus substrate delivery) are frequently changing.

4.3.3.4 Analysis of CAH Data: Conditions Required for Enhanced Biodegradation

The bar-line plots for IRZ-1 and RAP1-6T (Figures 4-31 and 4-34) demonstrate that the VOC concentrations decrease when substrate concentration increases as evidenced by TOC and specific conductance. Attempts to plot VOC concentrations as a function of TOC (not shown for brevity) did not yield a linear correlation. But a very clear correlation was observed between specific conductance (another measure of substrate influence) and TCE degradation in these two monitoring wells (see Figure 4-60).

This correlation between TCE degradation and substrate availability clearly does not hold for DCE degradation. This suggests that substrate is a necessary but not sufficient condition for enhanced biodegradation. For example from inspection of the bar-line plot for IRZ-1 (Figure 4-31) it is notable that good TCE treatment occurred in the spring and summer of 2001 but good treatment for both TCE and DCE did not occur until the spring and summer of 2002, despite similar TOC and specific conductance levels. Moreover there are no significant differences in pH, DO and ORP for well IRZ-1 between those time periods - but there is a significant difference in methane. Methane concentrations didn’t begin to increase until summer/fall of 2001. This suggests that it took almost a year of regular substrate injections and system adjustments to overcome the oxidative poise of more preferential electron acceptors (Suthersan,

2002) and reach methanogenic conditions at or upgradient of IRZ-1. This result is also in keeping with our theoretical understanding that enhanced biodegradation, especially the biodegradation of DCE is more favored under methanogenic conditions than sulfate-reducing conditions (Suthersan, 2002).

At RAP1-6T elevated methane levels were observed during the last two sampling periods; however this well never showed irrefutable evidence of DCE treatment (although there is some evidence). However as previously discussed RAP1-6T is on the fringe of the IRZ and did not experience the same sustained substrate loading IRZ-1 received.

Taken together this data set is consistent with a theoretical understanding in which both consistent substrate dosing and methanogenic conditions are required for optimal treatment (Suthersan, 2002). Bioremediation of CAHs can proceed at pilot- and full-scale via the formation of distinct subsurface zones characterized by a predominant terminal electron accepting process. Electron donor injected into the subsurface travels at a site specific rate downgradient while being utilized by differing bacterial communities which develop in response to the frequently varying, microbiologically processed electron donor(s) passing through them. Thus, starting with ERD implementation, what was likely a relatively uniform indigenous bacterial community diverges into “banded” zones characterized by differing dominant terminal electron acceptor processes. For example, near the line of injection wells, the bacterial community in an anoxic aquifer might be dominated by iron-reducing or nitrate-reducing bacteria that can utilize the sugars present in carbohydrate substrates immediately and are continually provided with an acceptable terminal electron acceptor by upgradient groundwater re-supply. Sulfate reducing and methanogenic and potentially dehalorespiring zones form further downgradient. Even further downgradient once all the substrate is consumed conditions gradually return to the ambient redox state. Dojka et al. documented this zonation concept on a vertical basis rather than a lateral basis at a site where a fuel hydrocarbon plume and a CAH plume commingled (Dojka et al., 1998).

As upgradient electron donors are depleted, downgradient zones are selected for and sized based on the presence of the next most energetically favorable electron acceptor available in the groundwater (the immediate area around the injection well itself is usually characterized by a very low redox condition). Downgradient zones can vary in their redox condition with the tendency being for increasingly negative redox values as distance from the injection well line increases. Even further downgradient all of the substrate is consumed, and thus the redox potential begins to increase again with distance. Redox is known to influence the degradation of lesser-chlorinated CAH daughter products whose accumulation would likely lead to a conclusion that the bioremediation effort is stalled at *cis*-1,2-DCE. One interpretation that can be drawn from the recent ITRC literature summary in Table 4-8 is that PCE and TCE can be reductively dechlorinated at higher redox values than are required for the successful reductive dechlorination of *cis*-1,2-DCE and VC. Therefore, the addition of sufficient carbohydrate substrate to drive redox values into the methanogenic or sulfate-reducing range in bacterial zones distant from the line of injection wells is required to achieve complete biodegradation.

4.3.3.5 Calculated Biodegradation Rates

In order to quantify the rate of decrease of constituents of concern (COC) during the demonstration, first-order attenuation rates were calculated for TCE, *cis*-DCE and VC using exponential regression methods. The first-order attenuation rate is described by the following relationship:

$$y = y_o e^{-kx}$$

where

y_o is the initial constituent concentration
y is the constituent concentration at time x
and k is the first-order degradation rate constant.

To account for decreases in concentration caused by dilution and dispersion, the data were normalized using bromide tracer data (see Section 4.3.3.2.1 for an explanation of dilution calculations). The use of a normalized data set results in a more conservative estimate of attenuation than would the raw data, and the resulting k can be attributed principally to biodegradation.

Rates were calculated at three well locations: IRZ-1 and RAP1-6T, the nearest downgradient monitoring wells screened within the injection interval, and at IRZ-INJ, the injection well. Bromide tracer data allowed for estimates of dilution even at the injection well, making it a reasonable monitoring point for evaluation of biodegradation rates. Initial concentrations were represented by an average of data collected within one year prior to the first molasses injection.

For each well, normalized concentration data were plotted versus time. An exponential regression was then fitted to a selected time interval, yielding an estimate of k and a correlation coefficient (R^2) for that interval. R^2 measures how well the regression equation represents the trend in the data. R^2 values range from 0 to 1; the closer to 1, the more accurate the representation. From the first-order rate constant, the attenuation half-life was calculated. Time intervals over which rates were calculated were selected to best represent periods of continuous and supportable biodegradation as follows:

- For IRZ-INJ, rates were calculated for the entire demonstration period, starting with the first injection in October 2000 (Figure 4-61). This approach is conservative because it incorporates the initial equilibration and desorption phases. A more detailed breakdown of the injection well data was not attempted because the available VOC data with associated bromide data (depicted in Figure 4-36) does not clearly define the equilibration period and desorption peak.
- For IRZ-1, TCE concentration decline attributable to biodegradation occurred primarily in the early part of the demonstration following the initial desorption peak, and ending in July 2001 (Figures 4-31 and 4-37 show the data and 4-62 the rate calculation). After this date, an apparent change in the flow field caused a disruption of the substrate delivery to IRZ-1 (see Figure 4-31) and a discontinuity in the VOC trend data. As discussed above *cis*-DCE biodegradation appears to require elevated methane in addition to TOC, which occurs at IRZ-1 starting in late 2001 (see Figure 4-31). The *cis*-DCE rate calculation is therefore based on data from October 2001 through October 2002 (see Figure 4-62). A VC biodegradation rate was not calculated at IRZ-1.

- At RAP1-6T, concentration declines in TCE and *cis*-DCE occurred early in demonstration starting at the initial desorption peak and ending in September 2001 (see Figures 4-34 and 4-35 for the data and 4-63 for the rate calculations). After this date, an apparent change in the flow field caused a disruption of the substrate delivery (see decline in TOC levels at RAP1-6T in Figure 4-34) and a discontinuity in the VOC trend data. A VC biodegradation rate was not calculated at RAP1-6T.

Degradation rates were also calculated for the pre-demonstration period using historical data from RAP1-6T (Figure 4-33 shows the data and Figure 4-64 the rate calculations). These calculations generally suggest that biodegradation was very slow or nonexistent before the demonstration. Clearly, biodegradation was occurring in this location prior to the demonstration, as evidenced by the presence of substantial concentrations of TCE daughter products. However, the fluctuations in the historical data also represent continuing influx from a source and changes in water levels, influenced in part by the groundwater pumping system. ***Thus this calculation is conservative (underestimates biodegradation) as are all of the calculations in this section because they assume that a fixed amount of CAH is present and degrades. We know from the discussions presented above that a source is existent in this area and thus that CAHs continue to be introduced from a solid phase or free phase source to the dissolved phase. The rate calculation however cannot take this into account because these interphase transfer rates are unknown.***

Results of the rate calculations are summarized in Table 4-9. Rates of degradation during treatment were substantially higher than in the pretreatment period for each of the three compounds considered.

Rates for all three of the compounds were higher at the downgradient wells than at the injection well. This is attributable partly to the time intervals over which the rates were calculated, and also to the repetition of injections. With repeated introductions of fresh substrate at the injection well, some biochemical conditions (e.g., highly reducing conditions including methanogenic) that are created with time (or distance) from the injection well are enhanced in downgradient locations relative to the substrate injection area.

Rates for other ERD sites where similar substrates have been used are provided for comparison. The sites for which data are listed are TCE sites, one with PCE as a parent compound, with degradation products including *cis*-DCE and VC. Total CAH concentrations at the sites ranged from 1.2 to 22 mg/L, under a variety of hydrogeologic conditions. The Hanscom site produced TCE degradation rates that fall within the range given for other sites. *Cis*-DCE rates for Hanscom were slower than for other sites; this is attributed in part to the inconsistent delivery of substrate to downgradient wells.

The rates in Table 4-9 are compared to rates given in Howard et al. (1991) for anaerobic, aqueous biodegradation, or natural attenuation. Calculated half-lives for TCE in the Hanscom demonstration ranged from 28 to 80 days, improving on the published range of 98 to 1653 days given by Howard et al. (1991). Rates for *cis*-DCE and VC were consistent with the published ranges.

Another comparison can be made with TCE attenuation rate constants compiled by EPA (1998) from Aronson and Howard (1997). Figure 4-65 shows the distribution of the rate constants, which represent natural attenuation of TCE as cited in published reports. EPA (1998) notes a likely bias toward high attenuation rates in this data. The Hanscom rates for TCE biodegradation in Table 4-9 are three to nine times the average published TCE natural attenuation rate constant of around 1/year.

4.3.4 Hydrogeology Discussion

4.3.4.1 Changes in Groundwater Flow Direction due to Changes in Pumping Rates

The ERD at Hanscom exhibited changes in groundwater flow that were not expected and led to complex patterns in substrate delivery and CAH concentration as discussed above. The most probable explanation for these changes is a combination of multiple sources and changing pumping patterns imprinted on top of a complex geology with relatively thin aquifer zones. A thorough discussion of the effect of groundwater extraction on flow direction in the demonstration area is provided in Appendix A-7 and is briefly presented in this section.

Under natural conditions, the flow direction in the three conductive geologic units is generally to the east-northeast (CH2M Hill, 1997). In the design of the pilot test, the influence of the recovery wells was taken into account, and a consistent southeasterly flow direction was assumed. However, flow patterns varied during the course of the demonstration. The variability of flow patterns is attributed to nearby pumping wells and the following hydrogeologic features of the lower sandy till, the unit in which the demonstration was conducted:

- The sandy till, the most productive of the three units, is semi-confined and continuous over the demonstration area as well as a larger area encompassing five production wells (BIW-1 through 4, BIW-6); and
- It is at most about 20 feet thick.

The confinement means that changes in withdrawals are expected to show effects much more quickly than in unconfined conditions. The quickness of reaction over larger areas is the result of the fact that in confined aquifers, unlike unconfined aquifers, the removal of large amounts of water is not needed to affect changes in head over relatively large areas because what is being transmitted is head, not water. In addition, the limited thickness of the till would result in transmittal of head changes to a larger area than in a thicker aquifer.

The locations of the recovery wells relative to the IRZ/ERD area are shown in Figure 3-1. Extraction histories for four of the five recovery wells are graphed in Figure 4-28. The most extreme variations in pumping rates since mid-2000 have occurred in wells BIW-3 and BIW-4. A detailed evaluation of well production and groundwater flow direction in the demonstration shows a correlation between the two, as discussed in Appendix A-7. In brief, changes in flow can be seen are corresponding to the following events:

- The BIW-3 shutdown in September and October 2000, and again in May 2001
- Increased pumping of BIW-4 starting in October 2001
- Decreases in BIW-3 and BIW-4 pumping rates in July through September 2002.

These changes in flow direction no doubt affected substrate delivery and thus treatment efficiency. The basic assumption made in setting up the injection and monitoring wells is that the direction of groundwater flow and hence contaminant and substrate transport is relatively stable in a southeasterly direction. While the reduction in the parent compound, TCE, has generally been favorable in the two monitoring wells that fell within the reactive zone, excursions from that trend occurred in late 2000 and in fall and winter 2001. The late 2000 changes, when a precipitous drop in TCE concentration was followed by a sharp rise (Figure 4-37), occurred when BIW-3 was first shut off, then increased to very high rate of withdrawal. The second occurred primarily in fall and winter 2001 and coincided with the increase in pumpage from BIW-4.

In summary, the changes in pumpage from wells BIW-3 and BIW-4 have induced changes in the flow regime at the IRZ/ERD area in the basal unit that help explain the variations in substrate delivery and treatment efficiency.

4.3.4.2 Groundwater Velocity Estimation

Based on preexisting data we estimated the groundwater flow velocity at the site to be 0.8 ft/day (ARCADIS Geraghty & Miller, 2000). Groundwater velocity observed in the demonstration area was calculated using the following three methods. A detailed explanation of each method can be found in Appendix A-7.

a) Based on average bromide concentrations observed at the first line of observation wells and the mass bromide loading rate at the injection well, a volumetric flow rate through the lower aquifer was estimated and used to derive a flow velocity. A velocity of 0.64 feet/day was calculated using this method.

b) The bromide arrival time at the first line of observation wells was used to calculate flow velocity. Using this method, the velocity was estimated to be between 0.30 feet/day and 1.57 feet/day.

c) Measured or estimated values of hydrogeologic characteristics were used to calculate flow velocity based on a variation of Darcy's Law. Using an average hydraulic conductivity of 19 feet/day, the flow velocity was calculated by this method to be 0.76 feet/day.

A discussion of the merits and limitations of each method is included in Appendix A-7. The values derived from the three methods are reasonably close, thus an average velocity during the demonstration period of approximately 0.80 ft/day is assumed.

4.3.5 Secondary Water Quality Issues

We recognize that while the substrate injected (molasses) and its breakdown products are generally nontoxic, it may elevate certain parameters in the water within the reactive zone. For example, by definition, any substrate used to enhance anaerobic bioremediation will elevate the BOD, a traditional measure of water quality. Furthermore, since we are intentionally creating reducing conditions within the reactive zone, this will necessarily alter the geochemistry of the reactive zone. This will make some soil mineral metals more mobile (more dissolved) and others less mobile (more inclined to the solid phase). Further information about these matters can be found in Sections 1.2, 2.1, 3.1 and 7 of the protocol document (Suthersan, 2002). An additional potential water quality issue, i.e., the metals content of the injected molasses solution, is addressed in Section 4.3.5.2. Although the injectate is not expected to introduce metals in harmful concentrations, the metals evaluations in this section also indirectly address this potential problem.

In general, it is believed that enhanced anaerobic in-situ bioremediation processes will reduce the mobility of many metals (indeed it has been successfully used for the treatment of many) but it will solubilize some other naturally occurring metals in the reactive zone (for example iron, manganese, and arsenic). However, even in solubilized form under anaerobic conditions, metals such as arsenic are substantially retarded by adsorption to the aquifer matrix. Furthermore, it is generally believed that they will be reprecipitated/immobilized downgradient of the reactive zone when the conditions return to their preexisting state (which for the purposes of this discussion is assumed to be aerobic). Similarly, reprecipitation/immobilization will occur within the IRZ area some time after system shutdown. Finally, we note that these reducing conditions are by no means unique to IRZ systems – they occur for example at sites of TPH releases and landfills as well.

Therefore, we agreed with ESTCP on a multi-step process to evaluate the following issues in the context of the Hanscom demonstration. Additional detail regarding each item is provided in Appendix A-8.

1. Review existing base monitoring data: Only very limited data were identified, and were deemed to be of little use to this demonstration.
2. Review mineralogy: This provides guidance for parameter selection and data interpretation but cannot be definitive.
3. Review data gathered to date on iron, manganese, COD and BOD
4. Expand the final monitoring round for this project to include total and dissolved metals plus TDS.
5. Incorporate analysis of data gathered on a related project: A large pilot scale study and a related simultaneous bench scale column study for Fort Devens, Massachusetts. Fort Devens and Hanscom are approximately 25 miles apart but their mineralogy may be somewhat different. The primary focus of the bench scale column study is the mobilization of arsenic during treatment of CAHs.
6. Expand the rebound monitoring to include total and dissolved metals plus TDS in wells in the heart of the treatment zone.

The results of these evaluations are discussed in detail in Appendix A-8. Key findings are briefly summarized below. It is noted that mentions of metals in this section and throughout this document also refer to the metalloids arsenic and selenium, as appropriate.

A number of parameters were found to be present at their highest concentrations at the injection well or in the reactive zone at the first line of downgradient monitoring wells (IRZ-1, RAP1-6T). Further downgradient, concentrations decreased to background levels at the next line of wells (IRZ-3, IRZ-4, IRZ-5, B242-GW). This trend was found for the following parameters:

- BOD and COD (Table 4-4) - as expected, elevated BOD and COD occurred at the injection well after injections began (BOD and COD are measures of injected molasses and its metabolic products just as TOC is).
- Hydrogen sulfide (Figure 4-40) is substantially elevated in the injection well and RAP1-6T as would be expected under anaerobic (sulfate reducing) conditions.
- TDS (Table 4-10) - like many of the other secondary water quality parameters, TDS was elevated in the reactive zone but decreased dramatically downgradient.
- Chloroform and carbon tetrachloride (Table 4-11) were likely introduced with the tap water used for injections (California Department of Health Services, Howard 1990). They were rarely detected and were never above MCLs.
- Ketones (acetone, 2-butanone, 2-hexanone, MIBK; see Table 4-11) were probably byproducts of molasses biodegradation, but all detections were below regulatory standards. The risks posed by these expected metabolic byproducts of the degradation of food grade carbon sources are very low in comparison to the risks posed by the chlorinated constituents that are targeted for remediation.
- Metals including iron, manganese, arsenic, beryllium, chromium, copper, lead, nickel, selenium, and zinc (Figures 4-66 through 4-69, Tables 4-12 and 4-13). The metals results indicate that secondary water quality impacts may occur within the reactive zone during implementation of ERD as a result of increased mobilization/solubilization of some metals. However, the effect appears to be limited to the injection area and to the extent of the strongly reducing zone. The metals data supports the concept that the affected metals, including arsenic, iron and manganese, are reprecipitated/immobilized downgradient of the reactive zone when conditions return to preexisting (less reducing) state. Similarly, it is expected that reprecipitation/ immobilization will occur within the IRZ area some time after system shutdown. Furthermore, the data supports the assertion that metals concentrations in the injectate do not create secondary water quality impacts.

4.3.5.1 Arsenic – Field and Bench Scale Observations from Another DoD IRZ Site

Similar issues have been discussed during the implementation of pilot tests performed for DoD at another Massachusetts site. At the Devens Reserve Forces Training Area, ARCADIS conducted bench-scale and field-scale ERD pilot tests that, while the primary objective was degradation of PCE, were designed in part to test for arsenic mobilization. The following discussion is summarized from the Devens ERD Pilot Test Evaluation Report (ARCADIS, November 2002).

There appear to be three primary triggers that can cause the release/solubilization of geogenic arsenic, including development of high pH (greater than 8.5), the presence of high concentrations of competing anions (such as phosphate, bicarbonate, or silicate), and development of reducing conditions at circumneutral pH.

Within the anaerobic and reducing IRZ created by ERD technology, there is evidence that some control on arsenic solubility can be realized through the formation of low-solubility arsenic sulfide compounds. However, it is expected that the primary control on arsenic solubility will be provided by adsorption to and co-precipitation with hydrous ferric (iron) oxides under ambient oxidizing conditions.

Under the Devens site's normal aerobic groundwater conditions, both dissolved-phase arsenic and iron concentrations were below laboratory detection limits. In the field pilot, arsenic was solubilized in the pilot study area at levels greater than both the current and proposed MCLs for arsenic. However, field tests supported the expectation that the presence of soluble arsenic will be limited to the boundaries of reducing zones created by the ERD technology. Once the original aerobic and oxidizing poise of those reducing zones is restored, it is expected that dissolved arsenic will decrease to non-detectable levels. ERD application was therefore considered appropriate for treatment of CAHs provided the temporary presence of arsenic was appropriately monitored and managed.

In the bench-scale treatability study (flow-through column study), the initial aerobic poise of each of three soil columns was overcome by passing reduced groundwater containing dissolved concentrations of arsenic, iron, and manganese through the columns. Measurements of the three metals/metalloids and DO and ORP were recorded at intervals as the water was applied to the columns. After reducing conditions had been achieved, the aerobic poise of two columns was restored using two different oxidation techniques (air injection and hydrogen peroxide injection). Based on the treatability study results, the following observations were made:

- Even under reducing conditions, the aquifer materials provided a significant level of control on arsenic solubility
- The injection of air or hydrogen peroxide in the field can create an aerobic environment (most suitable for controlling arsenic solubility)

Thus, both empirical data from the Devens site and published research indicate that arsenic solubility as it relates to the use of ERD can be controlled, mitigating concerns associated with use of the technology.

4.3.5.2 Metals in Molasses

Molasses in its pure form contains concentrations of several metals that may exceed water quality criteria. Published analyses of blackstrap molasses (US Sugar, 2001) and analyses of metals in molasses/water mixtures by ARCADIS are presented in Tables 4-14 and 4-15. The ARCADIS metals sample was from a commercial remediation site in Ohio where a different molasses source was used than at Hanscom, but the results should be similar for Hanscom. Also note that the water-to-molasses mixture used at the Ohio site was slightly more dilute than the Hanscom mixture. None of the metals detected exceeded available Federal MCLs, and would not if adjusted to match the more concentrated Hanscom mixture. In addition, the site metals groundwater data discussed above encompass any solute quality issues. In other words, the groundwater metals data in Section 4.3.5 show that metals, whether solubilized from the formation or introduced as a trace component of molasses (or both) were not problematic in this demonstration outside the reactive zone. On the basis of this evidence, we would not typically expect to see water quality impacts from the molasses injectate. However, this is a potential issue that should be briefly considered in the design phase of IRZ projects.

4.3.6 Other Observations

4.3.6.1 Reactive Zone Size and Residence Time

As discussed earlier, since the groundwater flow direction was on average more easterly than the planned southeasterly, the reactive zone was formed on the north side of the monitoring well array and it is highly probable that a large portion of the reactive zone formed to the north of well IRZ-1. We can estimate the maximum and minimum sizes of the reactive zone as follows:

<u>Width perpendicular to average groundwater flow direction:</u> The zone width was most clearly defined by RAP1-6T and IRZ-1. IRZ-1 received an adequate dose of substrate during most periods. RAP1-6T received an adequate dose of substrate for somewhat briefer times indicating that it was on the edge of the reactive zone, which is consistent with the potentiometric surface observations. Thus the minimum zone width was 20 feet and an estimated zone width, including the portion passing north of IRZ-1, was 40 feet.

<u>Length parallel to average flow direction:</u> The injection well, IRZ-1 and RAP1-6T were all clearly within the zone. The zone extended slightly upgradient of the injection well as evidenced by the decline in CAH concentrations. Well IRZ-5 was showing increased TOC and DOC by the end of the demonstration, suggesting that it was on the far edge of the zone. Thus the zone length is estimated as between 45 and 160 feet and likely was less than 100 feet.

<u>Depth (vertical):</u> The screened interval for the monitoring and injection wells was 10-15 feet. Near the end of the demonstration, some evidence was seen of influence in the upper aquifer and bedrock aquifer wells of the RAP1-6 cluster (see Figure 4-6 and Table 4-3). This suggests either further vertical mixing due to vertical gradients, seal leakage as discussed in Section 3.5.1, or diffusion. Thus the zone depth can be estimated as between 15 and 50 feet, but for all practical purposes the depth of the zone was equivalent to the thickness of the lower aquifer (18 to 25 feet).

These zone size definitions have been based on delivery of measurable substrate, which as discussed above is necessary for effective treatment. However, the effect on DO and ORP appears to have propagated much more widely (Figures 4-1 and 4-2).

To determine the residence time required to reduce CAHs in the demonstration area, it is necessary to separate out the travel time of the substrate between the injection well and the monitoring point, and the acclimation time required for microbial growth. The Hanscom results were also complicated by substrate distribution issues. At this site, there was a lag of 3 to 5 months (90 to 150 days) between the time of first injection and the beginning of enhanced TCE treatment at IRZ-1 and RAP1-6T. Travel time for the substrate to reach these wells is estimated at 53 days (see Section 4.3.4.2. and Appendix A-7), leaving approximately 40 to 100 days after substrate delivery for effective treatment to begin. The lag appeared to be due almost entirely to substrate distribution issues (see Figures 4-31 and 4-34) rather than biological acclimation. It is reasonable that no appreciable acclimation time was required at this site for enhanced TCE degradation because TCE biodegradation to DCE was already occurring prior to treatment.

Changes in DCE concentration took longer to occur. Although it is difficult to separate out the rates of production of DCE from TCE and of DCE degradation, the data suggests that at IRZ-1 DCE removal was not enhanced and ethene production increased until about 15 months after the first injection and was correlated with increases in methane concentration. This suggests that there was up to a year's lag beyond the time required to distribute substrate that may be due either to the successive consumption of electron acceptors required to reach methanogenic conditions, bacterial acclimation or both.

In summary, enhanced TCE treatment was thought to occur almost immediately upon sufficient substrate delivery. The residence time required for cis-1,2-DCE treatment, independent of travel and acclimation time, was not definitive, but is expected to be on the order of a few months for this site. The time required to achieve similar reductions in VC would be longer, but was not determined in the demonstration. However, the strong performance of the system under imperfect coverage suggests that a full-scale system with more homogeneous substrate distribution could achieve stringent cleanup goals within five years. Moreover, the demonstration area was apparently within a source zone, and would be expected to perform more efficiently in lower-concentration portions of the plume. A longer treatment zone parallel to groundwater flow in a plume-wide or multiple barrier application would also enhance full CAH treatment, and would likely be required at Hanscom to achieve MCLs.

An estimate was made of the number of injection points that would be required to treat the full extent of the lower aquifer plume in Figure 3-2. In hypothetically scaling up the system, it was assumed that a plume-wide application would be appropriate for the site, rather than another configuration such as a barrier or a limited source area application. A plume-wide application was also the basis of the cost analysis in Section 5, allowing comparison to common uses of pump-and-treat and other groundwater remediation technologies, as well as to most other ERD sites. Other geometries would likely require fewer injection points. In addition to the configuration, the following assumptions were made:

- A full-scale system would be run in lieu of pump and treat, or pump and treat system operation would be more steady, eliminating most of the variability in groundwater flow direction.
- The reactive zone size and residence time established for the demonstration would be representative of a system performing in a less variable flow field. This is conservative, since the amount of substrate delivered to the test plot would presumably treat the same CAH concentrations more effectively if it were dispersed in a narrower area.
- The targeted aquifer is of a fairly uniform thickness throughout the extent of the plume, similar to the 18 to 25 feet encountered in the demonstration area, and a single injection depth is adequate to treat the affected zone.
- The reactive zone size and residence time determined above are applicable for lower concentrations of CAHs found in the majority of the plume.

Based on a "treatment cell" emanating from an injection point measuring 40 feet wide by 100 feet long, or 4,000 square feet, and a total plume area of approximately 1,140,000 square feet (based on the plume map in Figure 3-2), approximately 285 injection points would be required to treat the full extent of the plume. This injection well spacing is consistent with recommendations made in Section 4.2.1 of the protocol document (Suthersan, 2000), in which typical spacing is cited at 20 to 50 feet transverse to flow direction and approximately 100 days travel time parallel to flow direction. Downgradient well spacing of 100 feet at the Hanscom site, divided by the groundwater velocity of 0.8 feet per day, represents a 125-day travel time. As discussed in the protocol document, well spacing parallel to groundwater flow is primarily a budgetary concern.

4.3.6.2 Utility of Hydrogen Data

Molasses is not directly consumed but rather goes to form a number of organic monomers, alcohols and organic acids, which in turn break down to form acetate and hydrogen, which serve as energy sources for methanogens involved in reductive dechlorination (Suthersan, 2002). It has been suggested that dissolved hydrogen can be a diagnostic parameter to monitor in groundwater from ERD monitoring wells, as it can suggest which microbially-mediated redox processes are predominating in the reactive zone. Though sampling and measurement of dissolved hydrogen from monitoring well groundwater is feasible, the results are subject to several potential problems. We believe that the cost of acquiring reliable hydrogen data is generally not justified at routine sites since the predominant redox processes in various zones can normally be delineated from other chemical measurements.

According to Chapelle 1999 "Significantly, each of these terminal electron-accepting processes (TEAPs) has a different affinity for H_2 uptake. CO_2 reduction (methanogenesis) has the lowest H_2 affinity, and observed steady-state H_2 concentrations in methanogenic aquifers are relatively high (5-30 nmol/L (nM)). Sulfate reduction has a slightly greater affinity for H_2 than methanogenesis and is observed to have lower characteristic H_2 concentrations (1-4 nM). Fe(III) reduction (0.2-0.8 nM) and nitrate reduction (<0.1 nM) have even greater affinities for H_2 and are observed to have progressively lower steady-state H_2 concentrations. Thus, concentrations of H_2 are a useful indicator of TEAPs in groundwater systems, particularly when interpreted in the context of electron acceptor (nitrate, Fe(III), and sulfate) availability and the presence of final products (Fe(II), sulfide, and methane) of microbial metabolism."

The measurement of dissolved hydrogen in groundwater is a two-step process: sampling and analysis. Both steps are critical and special care must be taken by the field crew during sampling to avoid potential contamination/interference of the sample. The most relevant sources of sample contamination/interference include:

- Contamination with atmospheric air
- Generation of hydrogen gas from well construction materials and techniques
- Generation of hydrogen gas resulting from choice of sampling pump employed

Standard low-flow sampling techniques are used as the basis for sampling groundwater for dissolved hydrogen analysis as hydrogen is an extremely volatile gas whose concentration in groundwater can be biased if exposed to the atmosphere. The use of a flow-through cell increases the protection of samples/measurements against atmospheric loss or contamination. Methodologies for hydrogen sampling used in this project were discussed in Section 3.5.7.1.2. A general discussion of hydrogen sampling and analysis methodologies can be found in Appendix C of the protocol document (Suthersan, 2002).

In addition to sampling technique, well construction is also critical. Wells with casings and/or screens constructed of iron-containing metals (e.g., cast iron, galvanized steel) have been shown to artificially generate dissolved hydrogen via the reduction of water by metallic iron under anoxic conditions (Chapelle et al., 1997). Wells constructed of PVC are recommended, although stainless steel and Teflon may also be acceptable (Microseeps, 2002; Bjerg, et al., 1997). In addition to well construction materials, the process of well installation itself has been shown to generate hydrogen gas, presumably from the disturbance of soil (Bjerg, 1997). For this reason, one to three months is recommended between well installation and the first hydrogen-monitoring event. Furthermore, the installation of wells or other site disturbances in the vicinity of a monitoring well may generate hydrogen from the soil, which can show up in the monitoring well. The radius of influence of such site disturbances as they relate to dissolved hydrogen measurements is most likely highly dependent on the specific characteristics of the site geology and is therefore difficult to generalize. However, noting nearby site disturbance activities is particularly salient if unusually/unexpectedly high hydrogen results are observed in an adjacent monitoring well.

The selection of sampling pump is also important and requires careful consideration of several factors including the pump operating characteristics (flow, head) and means of operation. Peristaltic pumps (which draw water under negative pressure) are generally preferred as they are low-flow, minimum turbulence/disturbance, and have been shown to enhance the gas-stripping process required during sampling (Chapelle 1997), though there may be times when conditions dictate that an alternative pump be used (e.g., the required head to be overcome may necessitate the use of a higher head pump). Positive pressure pumps such as piston or bladder pumps may be effectively used, although the surging operation of a bladder pump may cause the instantaneous flow rate to exceed those required to achieve liquid-gas hydrogen equilibrium during sampling. This limitation may be overcome by decreasing the duty-cycle of the bladder pump and/or by pumping into a surge tank with a peristaltic pump to feed the bubble strip sampling apparatus (Microseeps). Direct current submersible pumps should be avoided as the electrical current passing through the monitoring well may produce hydrogen gas from water via electrolysis (Chapelle 1997).

Hydrogen data from this demonstration is reported in Figure 4-70 and Tables 4-5 and 4-7. Many of the values from the June 2000 and March 2002 sampling rounds were reported as saturating the analytical process (> 50 nM/L). These values were above those conventionally associated with steady state concentrations in presence of various microbial communities. However in each of these rounds several samples, often ones that would be expected to be unimpacted by the reactive zone, such as RAP1-6R and B-239 showed substantially below saturation concentrations. Several possible explanations were considered for this trend in the data:

- Well construction methods were reviewed. Metals in the construction material were eliminated as a possible cause. However it is possible that since the June 2000 data was collected one month after well installation that metal drilling implements could have caused artifacts in that data, but this would not explain similar results in March 2002.
- Pumps used were reviewed and initially eliminated as a possible cause of artificially high values since the values occurred in some wells and not others and the pumps used were not of the type most suspected in hydrogen generation.
- Metal objects in the ground could not be eliminated as a possible cause since groundwater is relatively shallow and it is possible that pipes, fence posts or debris could be in contact with groundwater at some times.

We conferred with Dr. Francis Chapelle of USGS about the first two hydrogen data sets. He offered the opinion that the one round of post injection data may suggest that we are producing hydrogen faster than the microorganisms can use if and therefore it is building up to higher than expected levels. In general he believes that fermentation processes that produce hydrogen are more robust than the sulfate reducing or methanogenic processes that use hydrogen. He feels something (perhaps a co-contaminant) may be inhibiting hydrogen utilization here. He also noted that high hydrogen values had previously been observed in the presence of Aqueous Fire fighting foam (AFFF). Based on site history the presence of AFFF is possible.

We then performed a final round of hydrogen sampling in October 2002 sampling with an AC-powered Grundfos variable speed 2-inch submersible (centrifugal) pump. We requested that the laboratory dilute these samples as necessary to avoid detector saturation and thus extend the analytical range. In this instance, all of the results reported were above the saturation limit of the previous analyses. They ranged from 134 nM/L at RAP1-6T to 1452 nM/L at IRZ-1 and 1514 nM/L at IRZ-INJ. Since these values were judged to be unreasonably high, we resampled. Thus we repeated the sampling on October 29, 2002 in three selected wells using a peristaltic pump: B239, RAP1-6T and IRZ-1. The values obtained were 2.2 nM/L at B-239, 7.9 nM/L at RAP1-6T, and 9.7 nM/L at IRZ-1. Thus the values given in the tables and figures for this round should be considered very questionable. It appears that though it is DC current-driven submersible pumps that are associated with the most problems with hydrogen generation in the literature (Chapelle, 1997, p. 2876), that an AC-powered pump generated an artifact in this instance.

We conclude from this experience that the sampling of hydrogen during ERD projects may not be justified in most circumstances since:

- More reliable diagnostic information from which the predominant metabolic processes ongoing at the site can be inferred is available (measurements of alternate electron acceptors and the products of their use.
- Hydrogen sampling and analysis is relative complex and costly, subject to numerous potential artifacts and constrains pump selection substantially.

4.3.6.3 Fatty Acids

In the last sampling round in October 2002, fatty acids, which are metabolic byproducts of molasses degradation were sampled and analyzed in selected wells (Table 4-16). Acetic, propionic and butyric acids were found within the reactive zone but not upgradient. More information on the breakdown of molasses and other carbohydrates is presented in Section 1.3 of the protocol (Suthersan, 2002).

4.3.6.4 Microbial Population Characterization

Since there was strong evidence for natural attenuation at this site, no microbial characterization was performed prior to the pilot scale test. However, at the request of ESTCP, a microbial characterization was performed of the reactive zone during the final sampling round in October 2002 using groundwater samples. Phospholipid Fatty Acid Analysis, Denaturing Gradient Gel Electrophoresis and Targeted Gene Detection for Dehalococcoides ethenogenes (DHE) were performed. Samples were drawn from the generally upgradient well B239 and from the wells in the reactive zone or on its fringe - RAP1-6T and IRZ-1. The methods and results are presented and discussed in Appendix A-10. The main conclusions from this work were that:

- Good population numbers (for a groundwater sample) and good diversity were found in all samples.
- The samples from within the reactive zone showed less evidence of starvation then the upgradient sample.
- The samples within the reactive zone appeared to have more anaerobic populations.
- DHE was detected in the upgradient and RAP1-6T samples. Results from IRZ-1 were inconclusive due to interferences in the sample.

4.3.7 Comparison of Results with Objectives

Objectives for this demonstration were discussed in Section 4.1 and were grouped into primary and secondary objectives. A brief comparison of results with objectives is given in Table 4-2; longer discussions are provided in this section.

4.3.7.1 Primary Objectives

During the two-year demonstration, the data discussed below demonstrated highly effective, complete TCE removal in a source area that had a long history of fairly stable TCE concentrations before treatment. Multiple lines of evidence of complete treatment – a buildup of ethene, reduction in *cis*-DCE and no accumulation of VC was seen in the most effectively treated downgradient wells. Effective treatment was seen only where substantial substrate (molasses and its breakdown products) was observed in downgradient monitoring wells. The layout of the injection and monitoring well system was designed for a consistent southeasterly groundwater flow; however, during the demonstration period, the direction of flow varied with most observations suggesting an eastward flow direction. Thus, it is suspected that a larger IRZ was formed than what was observed, but that the monitoring well network was not positioned to completely delineate it.

This summary discussion of CAH treatment will focus primarily on the two monitoring wells that received substantial doses of substrate TOC, RAP 1-6T and IRZ-1 (Figure 4-5), and secondarily on the injection well, INZ-INJ. The two primary monitoring wells were also the only ones in the lower aquifer where substantially increased levels of methane were observed (Figure 4-30).

The best treatment results were observed at IRZ-1 (Figure 4-31). At this well, highly effective treatment of TCE was observed beginning in March 2001, 5 months after injections began and shortly after single injections with water pushes began (>95% reduction vs. pretest concentrations which greatly exceeds the objective of 80% reduction within one year). Substantial treatment of *cis*-1,2-DCE (eventually >85% reduction in pretest concentration) was not observed until March 2002, a year later, during a second period of high TOC delivery. Complete degradation was also shown by the substantial increase in ethene production in March 2002 (Figure 4-32), which continued to climb through the end of the demonstration, indicating that treatment effectiveness continued to increase after two years of system operation. Ethene concentrations at this well increased to more than 20 times the pretest value.

Well RAP1-6T had 14.5 years of relatively stable TCE, DCE and VC concentrations before the demonstration (Figure 4-33). A sharp decline in TCE was observed within 6 months of the beginning of injection, coinciding or slightly preceding the appearance of substrate (Figure 4-34). TCE levels for seven straight monitoring rounds were at 10% or less of the average of the proceeding 10 years (Figure 4-35), exceeding the 80% in one year treatment objective. Then the IRZ shifted away from this well as evidenced by the significant decline in TOC. As a result of this shift, TCE, DCE and VC concentrations rebounded. These concentrations dipped again when substrate levels increased, although it appears that the typical groundwater flow direction was somewhat more easterly rather than southeasterly as planned. Thus this well was probably at the fringe of the effective reactive zone for much of the demonstration period.

Although it is by definition a less accurate measure of the overall effectiveness of the reactive zone, it is useful to note that substantial evidence of effective treatment of all chlorinated species was seen at the injection well, even in data corrected for the dilution effect of the injected solution. Concentrations of TCE and VC were reduced by more than 95% for TCE and 85% for VC from May 2001 through the end of the demonstration. DCE decreased substantially less (at most about 75%). This suggests that although CAHs were being completely degraded, desorption from a localized source area (Figure 4-36) upgradient continued to impact the injection well.

The wells that did not get substantial, consistent doses of substrate showed no evidence of treatment or at most modest decreases in TCE only. This strengthens the conclusions that substrate availability is linked with improved biodegradation and that contaminant removal was due to enhanced biodegradation rather than displacement. At full scale a greater number of injection wells would provide overlap and would be less subject to changes in flow direction.

As discussed in Section 4.3.6.1, the residence time required to treat the source area CAH concentrations encountered in the demonstration area to Federal MCLs was not directly determined in the demonstration. However, the strong performance of the system under imperfect coverage suggests that a full-scale system with more homogeneous substrate distribution could achieve stringent cleanup goals within five years.

The data from RAP1-6T, IRZ-1 and the injection well do not show evidence of “accumulation” or “dead-ending” at DCE or VC (Figures 4-35 through 4-37). On the contrary, the data discussed above and especially the increases in ethene (Figures 4-32 and 4-42) show that complete degradation was achieved in these wells. Therefore the primary performance objectives were met for the wells within the reactive zone.

4.3.7.2 Secondary Objectives

In addition to the primary treatment effectiveness objectives discussed above, certain other objectives were established in the demonstration plan to improve understanding of the process (see Section 3.1 for more details):

Objective: Demonstrate the ability of the ERD to induce an anaerobic and reducing environment in groundwater.

Result: As shown by the DO, ORP, hydrogen sulfide and methane data (Figures 4-1, 4-2, 4-30 and 4-40), an anaerobic environment was created within the reactive zone.

Objective: Evaluate the ability of the ERD to desorb contaminants that are most likely sorbed to the aquifer materials.

Result: There is some evidence of a TCE desorption “hump” early in the demonstration (see Figure 4-37 for example). The fact that levels of CAHs at all of the wells in the demonstration zone before the test greatly exceeded the levels in upgradient well B239, and that pretest VOC concentrations increased from northwest to south east across the zone, suggests that desorption was ongoing within the zone even before treatment (see a more in-depth discussion in Section 3.4). Note also that the levels of CAHs at side-gradient or fringe wells such as IRZ-2 (Figure 4-48) were much higher than those in B239 (Figures 4-71 through 4-73) throughout the demonstration, also demonstrating that desorption was continuing through the demonstration. However, the rate of desorption is difficult to quantify and the increased desorption due to the IRZ is thus difficult to quantify (since the desorption and enhanced biodegradation processes occur simultaneously).

Objective: Evaluate degradation rates for CAHs in groundwater.

Result: Degradation rates calculated, as discussed in Section 4.3.3.5, were substantially enhanced over both the pretreatment rates and typical natural attenuation rates previously observed in the field at other sites. TCE degradation rates were shown to be in the range expected in enhanced in-situ bioremediation systems.

Objective: Determine the optimal strengths and frequency of reagent delivery for the site.

Result: Strengths and frequency of injection are discussed in Section 4.3.2.1. The first period of effective treatment occurred when the injection rate was approximately 125 lbs molasses per week in the single injection well. Injection rates ranged from 100 to 250 lbs molasses per week during the second period of highly effective treatment. However, due to changes in groundwater flow direction and flow rate that occurred during the demonstration, no single optimal strength and frequency can be defined. Rather, the optimal injection rate for full-scale system operation is better defined as that rate necessary to maintain the optimal substrate loading (shown by TOC and specific conductance) and microbial community (methanogenic) at the monitoring wells. These optimal conditions are defined and discussed in Section 4.3.3.4.

The demonstration plan discussed that the following target concentrations or ranges for various field parameters would be used as a guide to system operations:

- pH - > 4.5 s.u. in the injection wells; > 5.0 s.u. in the monitoring wells;
- DO - < 1.0 mg/L in both monitoring and injection wells;
- ORP - > -400 mV and < -250 mV in the injection wells; < -200 mV in the monitoring wells. For demonstration sites where reducing environments are identified in the groundwater prior to initiation of reagent injections, a target goal of lowering the ORP by 200 mV in the injection wells and 100 mV in the monitoring wells will be employed.
- TOC - > 500 mg/L and < 5,000 mg/L in the injection wells and > 50 mg/L in the monitoring wells. TOC in monitoring wells should be expected to decline with distance from the injection well.

- Specific conductance – order of magnitude increase in the injection wells; 20 to 50 % increase in monitoring wells.

The actual observed values for these parameters are presented in Section 4.3.2 and will only be briefly summarized here. The desired pH was achieved without difficulty in the monitoring wells within the demonstration zone, therefore somewhat lower pHs in the injection wells were tolerated to achieve acceptable TOC loadings.

DO was generally held to less than 1 mg/L in the monitoring wells; data for the injection well was believed to be unreliable because of “frothing” in that well. Occasional upward trends in DO were noted, which served as early warnings that the injection strategy needed to be adjusted.

ORP (Figure 4-2) was lower than –400 mV in the injection well for several months. ORP in the monitoring wells within the reactive zone held fairly steady between -100 and –200 mV during most of the demonstration. Although these were somewhat less reducing than the stated objective, as noted in Section 4.3.3.5, ORP measurement is inherently unreliable and methanogenic conditions and complete treatment were achieved at the observed ORP levels.

TOC >50 mg/L was achieved at times at the monitoring wells (see Figure 4-5). As discussed in Section 4.3, TOC levels above 10 mg/L at the monitoring wells were associated with effective treatment. TOC in the injection well was maintained over 500 mg/L throughout the demonstration. Although we stated a goal of less than 5,000 mg/L in the injection well in the demonstration plan, later experience at other sites caused us to modify that guidance to state that the upper limit is site-specific but generally around 9,000 mg/L (see Section 4.5 of the protocol [Suthersan, 2002]). Injection well TOC was generally but not always below 9,000 mg/L during this demonstration. However, as noted above, little or no pH change was noted at the monitoring wells and TOC at the monitoring wells was not excessive. Therefore, since this was a high flow site with only one injection well, high loadings at the injection well were used.

Specific conductance increased an order of magnitude in the injection well and more than 50% in the monitoring wells within the reactive zone. As shown in Figure 4-60, specific conductance increases were closely correlated to effective TCE treatment.

Thus, in summary, the reactive zone was generally operated within the expected ranges for the process monitoring parameters and all of the secondary objectives were met.

4.3.8 Technology Comparison

Based on the results of the demonstration as outlined in this document, the use of ERD to treat CAH impacts in groundwater via transformation to innocuous end-products has been demonstrated to be successful. In addition, as outlined in the work performed during the demonstration, the technology has provided many advantages over other conventional and emerging remediation techniques including the following:

- Ease of deployment – including very limited ‘hard’ design,
- Limited permitting & approvals,
- Ease of operations & maintenance,

- Flexibility,
- Limited health and safety risk directly related to the technology and reagent handling,
- Implementation with little impact to ongoing facility operations and/or future development activities.

These advantages as well as the competitive cost of application of the technology provide a convincing case for the applicability/desirability of the technology in a variety of application scenarios. However, the results of the demonstration illustrate some limitations of ERD application in comparison to other technologies. These limitations include the following:

- Speed at which desired reactions/treatment results can be expected to occur,
- Possible incomplete treatment of parent CAHs, and
- Possible solubilization of inorganics as a result of the reducing conditions.

Overall, these limitations are likely to be limited to a small percentage of sites and/or applications if the technology is implemented properly. However, they need to be carefully considered during both the technology selection and remedial design phases of the project to assure success.

Attached Table 4-17 contains a general comparison of ERD to several other common remediation technologies used for the treatment of CAHs, specifically, groundwater extraction & treatment, aquifer sparging, and chemical oxidation. This general comparison considers the relative effectiveness, reliability, speed and ease of use of each technique for comparison purposes.

Evaluation and comparison of ERD to other remedial techniques, specific to conditions at the Site can also be made. This comparison is especially valid at the Site given that the Base has undertaken numerous remediation projects including the use of groundwater extraction and treatment, vacuum-enhanced recovery (a modified version of groundwater extraction and treatment) and in-situ chemical oxidation. A discussion of these technologies as they relate to actual or potential application at the site is outlined below.

4.3.8.1 Groundwater Extraction and Treatment (Pump & Treat)

The use of groundwater extraction and treatment has been ongoing at the Site for many years and has provided valuable remediation progress for the overall restoration program at the Base. The dissolved CAH plumes have been stabilized and off-site migration and thus risks have been controlled.

However, it is clear that due to the portions of the Site underlain by low permeability geologic materials as well as the expansive size of the CAHs plumes at the Base, restoration of the site using pump and treat will require a very long time to achieve. This is clearly illustrated by the several locations in which high concentrations of CAHs are still present even after the lengthy pumping program. It is likely that a more cost effective approach would be to utilize ERD on source areas, and perhaps additional IRZs between source areas and the existing extraction well system. The goal would be to terminate use of the pump and treat system, and reduce constituent concentrations to levels suitable for application of monitored natural attenuation.

4.3.8.2 Aquifer Sparging

As outlined in the general analysis above, the use of sparging is often an effective means to remediate CAH impacts. However, at Hanscom this technology is technically unfeasible for the semi-confined aquifer since the confining unit would prevent recovery of the vapors resulting in the uncontrolled migration of gas-phase CAHs.

4.3.8.3 Chemical Oxidation

Given the in-situ nature of the technology, chemical oxidation would be expected to be a successful means of treating residual dissolved and adsorbed phase CAH impacts at the Site. Currently, the Air Force is in the process of evaluating this technology at the Base using permanganate as the oxidant. At the time of this report, performance data from these tests are unavailable.

It is expected that a chemical oxidant could be delivered to the impacted areas. Assuming this is the case, the suitability of chemical oxidation at the Site versus IRZ is likely an economic decision. Given the cost of the chemical reagents needed to not only oxidize the target compounds, but to overcome the natural reductive poise in the formation, the cost of chemical oxidation is expected to be high, if used for a full-scale plume treatment approach. More likely, chemical oxidation would be selected to play a limited or ‘surgical’ role in the overall restoration strategy using it in a program where it would be reserved for treatment of higher concentration areas or areas where rapid clean-up time periods outweighed cost concerns.

4.3.8.4 ERD

The results of the ERD demonstration at the Site indicate that the technology can be successfully applied and, if properly operated, can result in complete degradation of the CAHs present in the dissolved phase as well as the enhancement of desorption of adsorbed phase CAHs. Given the scope and limitation of the demonstration treatment to MCL’s was not demonstrated, although substantial degradation was. However, given ARCADIS’ experience at numerous other sites, as well as taking into account the lessons learned on this project, we are confident that the ERD technology can achieve those objectives.

In comparing the use of ERD to other technologies, the chief advantage of ERD is likely cost. The limited infrastructure required to deploy the technology as well as the low reagent costs will likely make ERD the least expensive means to address the residual impacts when implemented at full-scale.

4.3.9 Lessons Learned

ERD in an IRZ application has been applied at a broad range of sites since 1995. These sites have included a variety of constituents to be treated - including PCE, TCE, 1,1,1-TCA, carbon tetrachloride, pentachlorophenol, and chlorinated pesticides; various groundwater concentration ranges; and numerous hydrogeologic settings (including shale and karstic limestone bedrock, low permeability glacial tills and saprolite, and high permeability alluvium and glacial outwash environments).

As with all groundwater remediation activities both in-situ and ex-situ, the successful application of ERD relies mainly on sufficient and accurate hydrogeological information for the given site. The application of ERD to treat CAHs in groundwater at many sites located in varied in-situ hydrogeologic settings under different concentrations has provided a valuable knowledge base that has taught many lessons for future applications of the technology both at the pilot-and full-scale. These lessons learned are also applicable to applying other in-situ remedial techniques. Some specific lessons learned from the Hanscom demonstration are included below.

4.3.9.1 Substrate Dosing Required for Successful Treatment

As discussed in depth in Section 4.3, this demonstration clearly showed that a considerable concentration of substrate is required for successful treatment. As depicted in Figure 4-60, a specific conductance of 600 mS/cm (300 mS/cm above background) at the downgradient monitoring wells appears to be the threshold for successful treatment. Figures 4-31 and 4-34 suggest that successful treatment is usually associated with TOC values between 10 and 200 mg/L. This is in basic agreement with the guidance in the protocol document (Suthersan, 2002, Section 4.5) based on observations at many sites that 50-200 mg/L TOC in monitoring wells is ideal. They further suggest that methanogenic conditions as indicated by methane concentrations in excess of 1000 µg/L are associated with rapid, complete treatment.

4.3.9.2 Microbial Acclimation / The Role of Bioaugmentation

Following the addition of an electron donor, the microbiological community present at the site is required to acclimate to the changing aquifer conditions. During this interval, some originally prominent members of the community may decline in numbers or cease to exist entirely within the community at large. Other microorganisms that were previously present in relatively insignificant concentrations may find the changing conditions more suitable to their metabolic needs and expand in number. Once substrate has been delivered to an area within the aquifer, a period of several additional months is often required for the successive consumption of various electron acceptors, which in turn requires successive changes in the microbial community. It is ARCADIS’ experience that the implementation of the ERD technology typically results in a bacterial succession as described above where bacteria that are important for the biodegradation of CAHs become a functional part of the new bacterial community that is given rise by ERD implementation. The bacterial community present in the aquifer prior to carbohydrate injection is shifted towards species better adapted to a more reduced environment. In rare instances, ARCADIS has implemented bioaugmentation at ERD sites. Bioaugmentation is the introduction of a specific bacteria or mixture of bacteria to a site where it is felt that the community already in existence is lacking the capability to biodegrade a given contaminant.

At this site although there was a lag of 3-5 months between the time of first injection and the beginning of enhanced TCE treatment, this appeared to be due almost entirely to substrate distribution issues (see Figures 4-31 and 4-34) rather than biological acclimation. It is reasonable that no appreciable acclimation time was required at this site for enhanced TCE degradation because TCE biodegradation to DCE was already occurring prior to treatment.

Changes in DCE concentration took longer to occur. Although it is difficult to separate out the rates of production of DCE from TCE and of DCE degradation, the data suggests that at IRZ-1

DCE removal was not enhanced and ethene production increased until about 15 months after the first injection and was correlated with increases in methane concentration. This suggests that there was up to a year’s lag beyond the time required to distribute substrate that may be due either to the successive consumption of electron acceptors required to reach methanogenic conditions, bacterial acclimation or both.

4.3.9.3 Fermentation and Byproduct Formation

During the application of ERD, a highly reducing biogeochemical environment is generally created throughout the treatment zone. In addition, this zone will contain a large excess of organic carbon. During the application of ERD, most commonly when the contaminated aquifer possesses lower hydraulic conductivity (10-5 cm/sec [2.8 x 10-2 ft/day] or less), these conditions can result in the formation of organic acids in the groundwater as part of the degradation process. As a result of the formation of these acids, the ambient pH in the treatment zone can be lowered and in turn conditions conducive to fermentation-based reactions are then created. This environment can create low pH conditions that are detrimental to methanogenic bacteria.

The formation of undesirable byproducts including acetone and 2-butanone has been observed at sites where reagent dosing has commenced without careful monitoring of groundwater conditions near the injection wells. The occurrences of these byproducts are generally limited in extent and often sporadic in nature. It is expected that these ketones are also utilized by microbes in the IRZ. Almost all of these products are readily aerobically degradable as well and so are degraded on the downgradient edge of the ERD zone. Furthermore, almost all have higher risk-based limits (i.e., MCLs) than the target compounds of the ERD system. However, the possibility of production of these byproducts needs to be accounted for in the project planning stage. Therefore, the lessons learned regarding these potential occurrences are as follows:

- Careful and regular monitoring of groundwater within the treatment zone should be provided in order to ensure that pH levels are not depressed (pH < 5 at monitoring wells, pH < 4 in injection wells) and TOC levels are not excessive (site specific, but generally above 5,000 to 10,000 mg/L in injection wells).
- The remedial plan for application of ERD should be flexible enough to allow for modification of both the delivery frequency and mass of organic carbon delivered, preventing the build-up of organic carbon and creation of conditions amenable to creation of excessive amounts of these byproducts. Modifications in reagent delivery should be tied to regular pH and TOC monitoring in the treatment zone.

At Hanscom, as discussed in Section 4.3, pH changes in the monitoring wells were never significant but pH decreases in the injection well limited the substrate injection rate. The use of a clean water push was beneficial to disperse the injected TOC further beyond the injection well right after injection. This allowed the molasses injection rate to be substantially increased without further pH drops at the injection well. As discussed in Section 4.3.5, although ketones were generated as metabolic byproducts of molasses degradation, they did not pose an appreciable risk. At other sites, it may be desirable to add a buffer rather than using a water push (see Protocol Sections 4.1.2.1 and 6.2 [Suthersan, 2002]).

4.3.9.4 Pilot Test Design

This demonstration used one injection well with six monitoring wells in the downgradient target zone (arranged as two transects of three wells each). At this site substantial variability was observed in the groundwater flow direction vector. This resulted in marked changes over time in the substrate concentration at the most affected downgradient monitoring wells (RAP1-6T and IRZ-1). It also resulted in several downgradient monitoring wells not being impacted by the introduced substrate. Although it is desirable to have some downgradient monitoring wells outside of the reactive zone so that the radius of influence of a single injection well can be determined, installing too many uninfluenced pilot zone monitoring wells is not cost effective. Thus consideration should be given to an alternate test design with three injection wells in a transect and a smaller number of downgradient monitoring wells. This approach has the following advantages:

- It is less subject to changes in the groundwater flow direction vector once the demonstration begins, because the created zone is wider and thus the likelihood of a given monitoring well seeing wide variations in substrate concentration is lessened.
- It is less subject to errors in estimation of the exact direction of the average groundwater flow for similar reasons.
- The center of such a reactive zone would be more likely to maintain strongly reducing conditions because the wider zone would be less subject to diffusive mixing of electron acceptors from the sides.

However, the disadvantage of such a system is that it would be substantially more costly to estimate the radius of influence of each injection well (because a larger total number of wells would be needed if radius-of-influence data was vital).

4.3.9.5 Application in Areas of High Constituent Concentration/DNAPL

Given the inherent problems with the use of conventional remediation techniques in areas where the constituent concentrations are very high and/or where free phase constituent (DNAPL) may be present, ERD has been an attractive potential alternative for these settings (Yang and McCarty, 2000; Sharma and McCarty, 1996; Nielsen and Keasling, 1999; Cope and Hughes, 2001; Hughes, 2001). One benefit of applying ERD in high concentration regimes is related to the natural surfactant effect that usually accompanies this technology. When the groundwater equilibrium is altered, the transfer of more constituent mass from the free or adsorbed phase into the dissolved phase should be expected. An increase in the levels of dissolved constituents in groundwater results in an increase in a more treatable portion of the total CAH mass. This effect can be used by itself or in conjunction with other ongoing technologies (such as pump and treat) to reduce treatment life span and costs. Care needs to be taken that desorption does not result in the vertical or horizontal migration of elevated dissolved concentrations away from the treatment area (i.e., expansion of the constituent plume).

The possibility of enhancing migration to off-site areas or sensitive receptors is even more pronounced when applying ERD in a potential DNAPL environment. Therefore, prior to ERD application in these settings, a clear plan to address these possibilities must be available. This could include application of the technology on an “outside-in” approach in which the lower concentration areas downgradient of the areas of higher concentration are treated initially, or an approach in which the high concentration area is avoided altogether and the technology is applied in a containment role.

However, if properly accounted for, the possibility of concentration increases and/or migration of the impacts can be overcome and ERD can successfully be applied in these settings, especially when very high biological treatment rates can be established. The application of ERD in these areas will increase the levels of mass reduction in the subsurface, and once the initial disruption in phase equilibrium is overcome it can be expected that the technology will provide greater control of constituent migration from the source area.

Although it was not originally designed as a study of source zone treatment, evidence presented in Section 4.3 suggests that this demonstration was successfully operated in a source area.

4.3.9.6 Secondary Water Quality Impacts

As discussed in Section 4.3.5, secondary water quality impacts (including metals mobilization and high COD/BOD) were observed but as expected were limited to the area of the reactive zone and did not appear to be significant downgradient. Although ketones were generated as metabolic byproducts of molasses biodegradation, they did not appear to pose an appreciable risk.

5. Cost Assessment

5.1 Cost Reporting

An evaluation of costs specific to the demonstration and an estimate of unit costs will be provided in the Cost and Performance Report at the completion of the project, when final project financial information is available. At that time, we will also discuss costs associated with the demonstration that would be expected to differ at full-scale. A cost breakdown for a hypothetical case is provided in Section 5.2.4 and Table 5-1, using the Level 2 and 3 work breakdown structure given in U.S. Army Corps of Engineers, 2001 and elements of the cost tracking guidance provided in ESTCP, October 2002. Information is also presented in this section regarding cost comparisons between ERD and other technologies, based on our experience and that of others as presented in the literature.

5.2 Cost Analysis

In general, CAH plumes in groundwater may take one of three forms:

- Pure dissolved phase contamination
- Sorbed or emulsified source material with a dissolved phase plume
- Free phase (pumpable) DNAPL source with a dissolved phase plume.

The second case is by far the most common and is the condition assumed to exist at Hanscom. Cost analyses presented in this section are therefore geared toward this type of plume.

Additionally, ERD can be applied in at least three configurations – as a barrier, as a plume-wide treatment, and as a spot treatment of a source area. The choice of configuration for a given site depends on a variety of technical, economic, regulatory and risk factors. However, a common ERD approach is to treat the whole plume (above specified concentrations, leaving low-concentration fringes to attenuate naturally). This approach is assumed. Those analyses presented in this section are based on a dissolved phase plume with a sorbed, emulsified source area.

5.2.1 Cost Comparison

5.2.1.1 Cost Comparisons at Commercial Sites vs. Pump & Treat

The best way to estimate the potential benefit of an innovative remediation technology is to evaluate its cost at sites where it has been demonstrated alongside more conventional technologies. ARCADIS has extensive experience in replacement of pump and treat systems with IRZ technology. Some examples of actual and projected savings associated with these sites are listed in Table 5-2. The geometries of the listed CAH sites are inter-comparable, being generally plume-wide or multiple-transect applications (as opposed to single linear containment barriers) and not solely source area hot spot treatments. The CAH sites also generally fall into the category of dissolved phase plumes with sorbed source material. The same type of application would likely apply at the Hanscom plume.

5.2.1.2 Cost Comparisons at Commercial Sites vs. Other Innovative Technologies

Cost comparisons with other, more innovative technologies are available as well. For a South Carolina site, ARCADIS performed a cost comparison of several potentially applicable technologies (Table 5-3). The site contained a dissolved PCE/TCE plume in low-permeability, saprolitic soils. The comparison favorably portrays the application of an IRZ as a cost-competitive way of treating the contamination in the shortest predicted remedial interval.

DuPont has developed and published a computerized, controlled methodology to compare the costs of remediation for a standardized hypothetical site contaminated with PCE (Quinton et. al., 1997). The site was hypothetically established as being 1,000 ft long and 400 ft wide with free product. The DuPont study considered remediation duration, estimated engineering and flow/transport modeling costs, equipment costs, operation and maintenance, and monitoring costs when designing the controlled methodology. Following development of the comparison methodology, DuPont considered these treatment options: natural attenuation, substrate-enhanced anaerobic bioremediation (recirculating contaminated groundwater through the source area of the plume while injecting sodium benzoate as a carbon source), a biological substrate-enhanced anaerobic barrier (comparable to ARCADIS' IRZ technology), an *in-situ* permeable reactive barrier incorporating zero valent iron, and a pump and treat system with air stripping and carbon adsorption.

Natural attenuation, biological substrate-enhanced anaerobic barrier, *in-situ* permeable zero-valence iron reactive barrier, and pump and treat were evaluated as plume containment to be implemented 1,000 ft from the hypothetical spill zone. The scenario assumed that no free product removal technology would be implemented at the source area for containment technologies. Substrate-enhanced anaerobic bioremediation was evaluated as a technology that directly attacked the contamination in the spill zone.

To accurately determine and compare the costs of the listed technologies, DuPont included unit cost measure, cost elements making up the overall cost and period of time over which the cost is incurred in the actual remediation of the evaluation. The results of the evaluation from Quinton et al. are summarized in Table 5-4.

With the assumptions made during the DuPont evaluation, substrate-enhanced biobarrier (comparable to ARCADIS' IRZ technology) ranks third on cost. However, ARCADIS does not typically implement this technology as a containment technology in remedial situations where there is known to be free product in the source zone. In combination with a free product removal technology and a good knowledge of the subsurface hydrogeology, our company has found that it can more cost-effectively remove the free product and remediate the dissolved plume with our IRZ technology. It is our belief that, if DuPont's approach took this change in assumption into account, the substrate enhanced biobarrier evaluation would exchange places in the table with the recirculating source zone remedial approach to become the most cost-effective technology except natural attenuation.

Cost will certainly depend on scale, and generally the cost of the IRZ technology expressed per unit of CAH mass or gallon of water treated, decreases with increasing scale. This decrease occurs since transportation, mobilization, design and reporting costs are nearly fixed and can thus be spread over more units. This effect is generally similar for most remediation technologies, conventional or innovative.

5.2.2 Cost Basis

Three cost comparisons were made in the preceding section. In the first, ARCADIS compared projected costs for remediation of several sites based on estimated capital and O&M costs and the number of years required for each technology option to reach remedial goals, adjusted to present worth. The second (DuPont) cost comparison was constructed on a similar basis, but since it was based on a hypothetical site, was also extended to unit costs per volume of water and mass of contaminant treated. For a real site, the mass or volume of water treated in-situ is difficult to estimate with acceptable accuracy.

5.2.3 Cost Drivers

Section 2.3 provides a general discussion of cost factors associated with ERD. An even more extensive discussion of ERD cost drivers has recently been published as Sections 4 through 6 of the protocol document (Suthersan, 2002). Although a project-specific cost analysis has yet to be conducted (but will be provided in the cost and performance report), anticipated cost drivers are briefly summarized as follows:

- The majority of the costs related to reagent injection are related to labor (including preparation and support), temporary and permanent equipment, type of application (source reduction vs. plume-wide treatment), etc. The cost of the reagent material is relatively insignificant. The typical cost per pound of TOC delivered is as outlined on Table 2-2.
- Based on our experience and analysis, the two largest cost factors for ERD implementation are the injection well installation and the O&M associated with reagent injections. Three other factors that need to be given special consideration during design in order to develop the most cost effective approach for site remediation are:
    - Plume size
    - Depth of target zone
    - Magnitude of groundwater flux

5.2.4 Life-Cycle Costs

Extensive information about cost experience in actual practice with this technology has been provided in Appendix A of the protocol document (Suthersan, 2002). These costs are broken down into capital and O&M only.

A more detailed breakdown of life-cycle costs for a hypothetical, typical site is provided in Table 5-1, using the Level 2 and 3 work breakdown structure given in U.S. Army Corps of Engineers, 2001. The hypothetical example assumes the following conditions:

> *The hypothetical site is a commercial property with a TCE plume. The TCE exists largely in the dissolved phase, but residual source material remains in a sorbed, emulsified state; no pooled DNAPL remains. A combination of ERD and monitored natural attenuation (MNA) will be used to achieve cleanup standards. The ERD is targeted for the portion of the plume where TCE concentrations range from 1 to 5 mg/L. This area is approximately 400 feet in length, 100 feet in width, 20 feet in thickness, and extends to a depth of 50 feet. Groundwater velocity is 0.5 feet/day.*

> *The portion of the plume targeted for ERD is to be treated with a 10% molasses solution, injected through 25 injection wells. Injections are performed monthly for the first two years of treatment, using mobile, trailer-mounted injection equipment. The rate of injection is then reduced to bi-monthly for three additional years. The project duration is five years from the initiation of the ERD program, including three years of MNA. MNA costs are not presented here.*

Table 5-1 includes capital, operating and regulatory (permitting and reporting) costs. Since costs are based on complete destruction of CAHs, no future liability costs are included.

The hypothetical site represents a whole-plume application where no DNAPL is present in the source area. This approach is potentially appropriate for the Hanscom plume, where no separate phase CAH is thought to exist. Similar applications at real sites are represented in Table 5-5.

The duration of ERD injections and MNA are of course different for each site and dependent on site conditions. The example of five years of injections, followed by three years of MNA, is typical, based on ARCADIS' experience. Treatment at many sites is much faster. At least six ARCADIS ERD sites have succeeded in reaching MCLs for target CAHs or even obtaining closure certifications within 18 months to 2.5 years after the initiation of ERD (see Appendix sections A-2.4 and A-2.8 of the protocol document [Suthersan, 2002]; Panhorst et al. [2002]; and Payne et al. [2001]).

Unit costs for remediation of the hypothetical plume using ERD were estimated on a basis of gallons of water treated. Two estimation methods were used: first, assuming that the initial volume of contaminated water is the total volume to be treated, and second, considering the flux of water through the plume area for the five-year duration of treatment. This approach provides a conservative range of costs.

- For a an aquifer with total porosity of 0.3, the initial volume of groundwater in the hypothetical plume is 240,000 cubic feet, or 1,795,200 gallons. With a total project cost of $680,298 (from Table 5-1), the cost per initial gallon of water treated is $0.39. This cost is overestimated, since desorption and other effects require treatment of several pore volumes of water, thereby substantially increasing the volume of water that must be treated.

- The cross-section of the plume perpendicular to groundwater flow is 100 feet wide and 20 feet thick, for a cross-sectional area of 2,000 square feet. At a velocity of 0.5 ft/day, the flux through the cross-section is 300 cubic ft/day. Over the 5 years (1,825 days) of treatment, 547,500 cubic feet, or 4,095,300 gallons of water will flow through the cross sectional area. With a total project cost of $680,298 (from Table 5-1), the cost per gallon of water treated is $0.17. This estimate provides a lower bound on the potential range of unit costs.

Conditions at the Hanscom site differed from the hypothetical cost example in having a variable flow direction, thereby affecting the distribution of substrate and the volume of substrate used. Under these circumstances, the relative substrate cost was likely higher than at the average ERD site, or at the hypothetical site discussed below. In particular, the hypothetical example uses 20 gallons of molasses per well per injection (see Table 5-1), with injections occurring at one-month intervals, eventually decreasing to bimonthly intervals. In contrast, the overall molasses use at Hanscom averaged just under two injections per month, at 27 gallons of molasses per injection. Without the variability in groundwater flow direction, less molasses would have been required. Hanscom's flow velocity was also higher than at the hypothetical site (0.8 ft/day vs. 0.5 ft/day), which increases groundwater flux and the required molasses feed rate. In a full-scale application at Hanscom, it is expected that the flow field could be controlled (e.g., by shutdown or more uniform operation of the pump and treat system) and/or that substrate distribution would be less problematic due to broader coverage of the area to be remediated by multiple injection points. Thus, the injection parameters used in the hypothetical example are considered typical based on ARCADIS' experience, and are not solely based on the Hanscom example.

Based on ARCADIS' experience, actual project costs have ranged from approximately $75,000 for a small-scale application and/or pilot study or demonstration-scale project to $2,000,000 for a large plume treatment with a fully automated reagent injection system. Table 5-5 presents a selection of cost examples with concentration and size information. The full-scale system for the automated site included installation of over 100 reagent injection wells to provide aggressive plume-wide treatment.

Operating costs (including reagent injection, monitoring and reporting) are generally on the order of $50,000 to $100,000 per year. The percentage of the total costs associated with the reagent injections is typically greater than 50%. On the other hand, the actual cost of the reagent itself typically represents less than 10% of the total project cost.

The cost data presented in Table 5-5 clearly illustrate the effective nature of the ERD technology in addressing CAH contamination in groundwater. For example, two sites have been completed with "no further action" notifications from the regulatory agencies, for less than $500,000 each.

6. Implementation Issues

6.1 Environmental Checklist

Potential regulations that affect the ERD demonstration are limited to those addressing *in-situ* remediation technologies. These regulations include underground injection control (UIC) permit issues and the products of the ERD treatment process. There are no unusual issues involving the transport, storage or disposal of wastes and treatment residuals. The standard issues of drill cuttings produced during injection well installation and purge water produced during well sampling may apply.

The amount of interaction with regulatory agencies required to execute the ERD projects is sometimes substantially greater than with traditional technologies, until a particular regulatory agency becomes familiar and comfortable with these technologies. However, the technology has been successfully permitted in numerous jurisdictions and the regulatory community's experience base is growing. ARCADIS currently has more than 130 IRZ projects in 26 states that are complete or underway. Of these, 30 are full-scale implementations, and five have achieved closure status. Reagents approved for use at various ERD sites include molasses, corn syrup and whey.

Many states regulate the injection of materials into the subsurface and may require a Safe Drinking Water Act-mandated UIC permit prior to implementing the technology. The UIC permit includes information regarding the chemical nature of the substrate solution, and addresses potential concerns with water quality resulting from the injection process. Typically, the carbohydrate reagents recommended are food-grade, contributing to the rapid acceptance of the technology. UIC permitting for injection of carbohydrates is generally waived or is implemented with minimal paperwork (for example, permitting by rule). This issue is not considered to be a major impediment to ERD implementation.

Previous experience with state regulatory agencies where ERD technology has been performed indicates that an initial meeting to establish the proposed course of action for the project is the most effective process. The concerns of the UIC permit staff at state regulatory agencies must be addressed at the onset of the project to avoid delays. Usually, the information required to satisfy the requirements of the UIC permits is readily available, and should not represent a major regulatory hurdle. Continued close communications with the regulatory agencies during the planning and execution of ERD greatly increase the potential for a successful demonstration. A teaming relationship with the local environmental regulatory agencies is important to technology success.

Public participation during the technology process should be addressed on a site-specific basis. Inquiries on behalf of public entities should be addressed in a timely manner by the project management. The ERD technology is a relatively straightforward and non-threatening process, and thus it is anticipated that any public communications will be favorably received.

6.2 Other Regulatory Issues

Hanscom AFB is a CERCLA (Superfund) Site, regulated by the United States Environmental Protection Agency (USEPA). Remedial Investigations and Remedial Actions have been ongoing at the facility since 1985. A pre-NPL "Remedial Action Plan" for what is now NPL Operable Unit 1 (which includes Site 1) was approved and implemented in 1987. Subsequently, in October 2000, an Interim Record of Decision was issued for NPL Operable Unit 1 to continue operation of the existing dynamic groundwater collection and treatment system. MADEP concurred with the Interim Record of Decision.

Interactions with USEPA and MADEP are handled by Hanscom AFB personnel. Correspondence, reports, and work plans are routed through Hanscom AFB personnel to the regulatory agencies. Approval of the project work plan was granted by the USEPA in a January 4, 2000 letter (Michael Barry of USEPA to Tom Best of Hanscom AFB), with MADEP deferral. Because of the demonstration status of the project, EPA approved its implementation without a UIC permit. The addition of a potassium bromide tracer to the reagent was also approved by the USEPA in a separate communication.

A formal briefing on the progress of the project has not yet been conducted with regulators. However, summary information was recently provided to the USEPA in Hanscom’s *Five Year Review Report* (August 2002), with which USEPA has indicated its concurrence. The report recommended continuance of ongoing efforts in the demonstration area to reduce source area contamination and to support a final groundwater remedy.

Since this demonstration was entirely within the Hanscom Field/Hanscom AFB boundaries and not in a residential area there was no formal public participation requirement. Hanscom AFB personnel are responsible for attending and presenting at regularly scheduled public meetings the overall remediation problem at the Base. Hanscom AFB communicates environmental information to the public through its website http://www.hanscom.af.mil/ and through the availability of documents at the Bedford Town Library. Hanscom also has a Restoration Advisory Board (RAB) and works with officials in the four surrounding communities on environmental issues.

6.3 End-User Issues

The IRZ/ERD technology is being implemented at over 130 commercial and government-owned facilities and, within the limits recommended in Table 3-2, may potentially be applied to any groundwater CAH plume. CAH contamination is a common remediation concern at DoD installations. EPA has estimated that more than 3,000 DoD sites in the US alone are contaminated with chlorinated hydrocarbons. The information in the FY 2001 DERP Annual Report to congress, which is organized by site type, was used to estimate that DoD has 6,800 total solvent sites of which 2,300 are sites “in progress”. ARCADIS’ applications of ERD to Federal sites are detailed in Section 6.3.3.

6.3.1 Secondary Water Quality and Gas Production Issues

Secondary water quality and gas production issues as they relate to stakeholders and end-users are discussed in detail in Section 1.4. Briefly, the following issues were identified:

- The production of intermediate products of CAHs as the ERD process converts more highly chlorinated CAHs to less chlorinated and eventually non-chlorinated end products. The cascading reactions can result in the production of vinyl chloride. The production of vinyl chloride or other intermediate products is considered a temporary situation and does not represent a major impediment to the technology but should be monitored during application of the technology.

- Gases such as methane, hydrogen sulfide, and carbon dioxide may be produced and may potentially migrate and/or accumulate in the vadose zone. Since engineering solutions are fairly easily implemented, this issue is not considered to be a major impediment to technology implementation.

- The by-products of substrate consumption may include metals mobilized from the solid phase, COD, BOD, TDS, taste, odor, and sulfides. However, these impacts are typically limited to the reactive zone itself. Furthermore, it is generally believed that metals will be reprecipitated or immobilized downgradient of the reactive zone when the conditions return to their preexisting state and within the IRZ area some time after system shutdown.

- Molasses itself is a potential source of metals. The molasses-water mixture did not produce secondary water quality issues in this demonstration (see Section 4.3.5). However, this is a potential issue that should be briefly considered in the design phase for IRZ projects. The paucity of available data suggests that further work should be done to explore the metallic content of different sources of molasses.

Thus the potential for secondary water quality impacts needs to be fully identified and addressed during design and in consultation with all applicable regulatory agencies and the public.

6.3.2 Procurement and Implementation Issues

Equipment required for technology implementation as applied at Hanscom, described in Sections 2.3 and 3.5.1, is non-specialized and readily available. System design must be customized for each application to account for regulatory and site conditions, hydrogeological and geochemical characteristics, but the elements of a batch-fed IRZ/ERD are available commercially-off-the-shelf (COTS) and through subcontract with laboratories, drilling contractors, etc. As summarized in Table 4-2, ERD technology is relatively easy to implement and beyond the design phase and should generally only require environmental technicians for field implementation and maintenance. Automated systems and those involving extraction/ reinjection systems require custom design, and the ease of implementation of such systems is design-dependent.

The primary scale-up issue is the addition of injection wells to expand the IRZ, based on the geometry of the IRZ as determined during the field pilot test. If the number of injection wells required is excessive, or if drilling costs are prohibitive due to depth or difficult geological conditions, scaling up could pose significant hurdles. However, such barriers are usually foreseen before a pilot test is implemented.

Licensing is required to apply the technology. ARCADIS is the owner of Contractor Patented Technology for the in-situ addition of carbohydrate substrate material to create reactive zones for the removal of chlorinated hydrocarbons from groundwater as set forth in U.S. Patent Nos. 6,143,177 and 6,322,700. ARCADIS and the U.S. Government have agreed for ARCADIS to grant to the Government a paid up, non-exclusive limited license for government owned facilities only (this agreement is related to the demonstration effort "In situ Substrate Addition to Create Reactive Zones for Treatment of Chlorinated Aliphatic Hydrocarbons" under Contract No. F41624-99-C-8032). No rights to assign, sublicense or other ownership interests are to be conveyed therein, nor shall the License apply to any other patented technology that is owned or licensed by ARCADIS. To discuss application of this technology at government sites please contact "Government contact name and #" and Chris Lutes of ARCADIS in Durham, NC at 919-544-4535 or clutes@arcadis-us.com. For commercial application please contact ARCADIS only.

The technology was customized for the demonstration only in the sense that all sites require a customized system design and adjustment of operations as monitoring data is gathered. As implied by the widespread existing use of the technology (see Section 2.2), it has already been successfully commercialized and transferred.

6.3.3 Transition

The in situ reactive zone (IRZ) bioremediation technology discussed herein was developed primarily in the private and sector and has been applied (at more than 130 sites) to treat metals and CAHs. These sites involved regulators and a variety of site conditions in several different geographic areas of the country. The technology is mature as a plume remediation strategy or barrier strategy and ready to transition to commercial application in the DoD. It has been used successfully in "source" type zones up to 150 mg/L initial TCE (see Section A.2.13 of the protocol document [Suthersan, 2002]). It is applicable to a wide range of contaminants and geological conditions (see Sections 1 and 2 of Suthersan, 2002). It is not, however, a "silver bullet" applicable to all sites and all contaminants and/or mixtures of contaminants. Additional demonstrations are not necessary for treatment of groundwater plumes but would provide useful data to further elucidate applicability to varying conditions and/or contaminants. Additional demonstrations are desirable to evaluate potential to various source zone architectures (for example sites with DNAPL entrapped in soil pores or present in fractured bedrock) and to evaluate different delivery mechanisms, such as recirculation wells, for deeper/thicker plumes). Additional demonstrations are also desirable to extend the technique to additional contaminants such as explosives and perchlorates. ARCADIS has demonstrated that the technique is applicable to a wide variety of subsurface conditions. However, experienced personnel familiar with IRZ must carefully evaluate each site in order to identify conditions, including adverse geochemistry, that could impact remedial design.

Finalization of the protocol "Technical Protocol for Using Soluble Carbohydrates to Enhance Reductive Dechlorination of Chlorinated Aliphatic Hydrocarbons" occurred in December 2002 and will be a major technology transfer step. While not a demonstration need, collection of case histories will provide a useful guidance tool. This process has begun as Appendix A of the protocol (Suthersan, 2002) and is expected to continue during DoD's effort to prepare the

“Principles and Practices of Enhanced Anaerobic Bioremediation” document now ongoing with ARCADIS participation.

As inventor of the technique (and current patent holder), ARCADIS is the most experienced firm to apply soluble carbohydrates for the enhancement of anaerobic biodegradation. ARCADIS is already aggressively and successfully seeking to roll out the IRZ technique at other DoD and DOE facilities. ARCADIS has the following IRZ projects underway at Federal facilities:

- A pilot scale application underway this year at Fort Devens, Massachusetts (see Section 4.3.5.1) under a guaranteed fixed price contract
- A recently completed pilot study for the Navy at Naval Weapons Industrial Reserve Plant, Dallas, Texas, (see Enhanced In-Situ Biotransformation Pilot Study Report, to NFESC March 29, 2002)
- Two sites at Lompoc Federal Penitentiary where an IRZ pilot study that has been submitted for regulatory approval at a guaranteed performance contracting site (this is a DoD/FORSCOM project it was a disciplinary barracks and got transferred to Bureau Of Prisons during BRAC)
- A bench scale study of IRZ for Uranium underway under a contract with DOE NETL using samples from Fernald
- Under a recently signed guarantied fixed price contract at Fort Leavenworth KS we are planning application at two sites - the work plans for these are under EPA and state review
- A planned application under a recently signed guaranteed fixed price AFCEE task order for Charleston AFB in South Carolina
- A demonstration for Bechtel Jacobs LLC at the DOE/Piketon facility for both TCE and radionuclides
- A demonstration for energetics that has been contracted through AEC/Plexus for Milan Army Ammunition Plant in Tennessee.

Perhaps one of the most likely sources of funding will be redirection of funding as IRZ approaches are substituted, with regulatory approval, for marginal or ineffective pump and treat systems. The Army’s Groundwater Effectiveness Technical Evaluation Review (GWETER) program managed by the Army Environmental Center (AEC) and supported by ARCADIS demonstrates how this process works. Under this contract, ARCADIS has performed life-cycle analyses and expert technology reviews of existing groundwater pump and treat systems at ten active and inactive (Army Base Realignment and Closure [BRAC]) sites to evaluate whether or not existing remediation systems are appropriate, efficient and cost effective in achieving site-specific goals. Success include Former Fort Ord (Monterey, CA) where plans are under way for remediating a large chlorinated plume using in-situ technologies, and an in-situ pilot test at Milan Army Depot (Milan, TN) on explosives (RDX, TNT, HMX) in groundwater. The Milan project will demonstrate extension of IRZ to destroy explosives. As noted previously, there are many potential opportunities under Army, Navy and Air Force jurisdiction to substitute IRZ for existing pump and treat systems and realize substantial savings and a shorter path to closure. The action remains for DoD contracting groups and installation restoration program managers to seek more effective solutions.

As noted previously, IRZ is a bioremediation technique utilizing an electron donor to effect conditions needed to achieve treatment objectives in situ. While IRZ is applicable to a wide variety of sites and contaminants, expert knowledge is necessary to choose those situations with greatest potential for performance success and treatment cost reduction. In the last few years the DoD has extended performance based contracts (PBCs) to include remediation projects. PBCs are nearly ideal approaches for transfer of IRZ and other similar technologies to the user. A well-written PBC scope of work describes treatment objectives but leaves remedy choice to potential remediation service providers. This paradigm shift away from “cost plus” approaches leaves DoD officials in control as performance is monitored against various milestones set by the firm providing remediation services while allowing the private sector firm flexibility to work with regulators to choose remedies that best meet site specific requirements and optimize profitability of the job. The Army, Navy and Air Force are all working PBC remediation strategies. Additional procurement guidance will be needed as lessons learned are applied. Potential for cost savings are substantial. The need to transition to PBC approaches and realize maximum benefit from PBC approaches is urgent.

This demonstration project was performed by ARCADIS. ARCADIS is a private sector firm providing remediation services to a wide variety of industrial and government clients. The work was funded in part by ESTCP and AFCEE and managed by AFCEE. ARCADIS is already aggressively marketing IRZ to industry and government sectors and seeking other private sector organizations interesting in adding this technology to their tool kit. To date ARCADIS has implemented IRZ solutions at more than 130 sites in the U. S. and abroad and is working with other private sector partners to facilitate broader application of the technique.

ARCADIS will continue ongoing IRZ marketing efforts to both private sector and government clients. The firm’s objective has never been to be the low cost provider but to provide best and most cost effective solutions. IRZ is an integral part of ARCADIS’ GRiP® fixed price remediation contracting approach. Ongoing efforts at AFCEE, US Army Corps of Engineers (USACE) Omaha District, Army FORSCOM and elsewhere all support IRZ technology transfer efforts by emphasizing performance and price vs. low unit cost plus fee. Contracts are already in place with these agencies that encourage adoption of innovative technologies like IRZ. Increased utilization of these contracts should be encouraged. In addition ARCADIS is very willing to cooperate with other firms in implementing this technology under other government contracts at sites where they are the lead consultant.

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8. Points of Contact

POINT OF CONTACT	ORGANIZATION	Phone/Fax/Email	Role in Project
Dr. Andrea Leeson Program Manager, Cleanup	ESTCP 901 North Stuart Street Suite 303 Arlington, VA 22203	703-696-2118 (ph) 703-696-2114 (fax) andrea.leeson@osd.mil	ESTCP Lead
Jerry Hansen Project Manager	AFCEE Technology Transfer Div. 3207 Sydney Brooks Brooks AFB, TX 78235-5344	210-536-4353, DSN 240-4353 (ph) 210-536-4330, DSN 240-4330 (fax) Jerry.Hansen@brooks.af.mil	AFCEE Lead
Pete Palmer, P.E., P.G.	ARCADIS G&M, Inc. 14497 North Dale Mabry Hwy, Suite 115 Tampa, FL 33618	813-961-1921 (ph) 813-961-2599 (fax) ppalmer@arcadis-us.com	Principal Investigator
Christopher C. Lutes	ARCADIS G&M, Inc. 4915 Prospectus Drive Suite F Durham, NC 27713	919-544-4535 (ph) 919-544-5690 (fax) clutes@arcadis-us.com	Project Manager/Lead
Thomas W. Best Environmental Engr.	Hanscom AFB 66 CES/CEVR 120 Grenier Street Hanscom AFB, MA 01731	781-377-4495, DSN 478-4495 (ph) 781-377-8545, DSN 478-8545 (fax) Thomas.Best@hanscom.al.mil	Hanscom AFB Site Contact
Michael Berry Remedial Project Manager	Federal Facilities Superfund Section U.S. EPA, Region 1 1 Congress Street, Suite 1100 (HBT) Boston, MA 02114-2023	617-918-1344 (ph) barry.michael@epa.gov	Regulatory Contact
Glen Gordon, P.E.	ARCADIS G&M, Inc. Wannalancit Office & Tech. Ctr 175 Cabot Street, Suite 5400 Lowell, MA 01854	918-937-9999 ggordon@arcadis-us.com	ARCADIS G&M Base Liaison

Project Lead Signature:

______________________________________ ___________________________

Christopher C. Lutes, ARCADIS G&M, Inc. Date

Figures

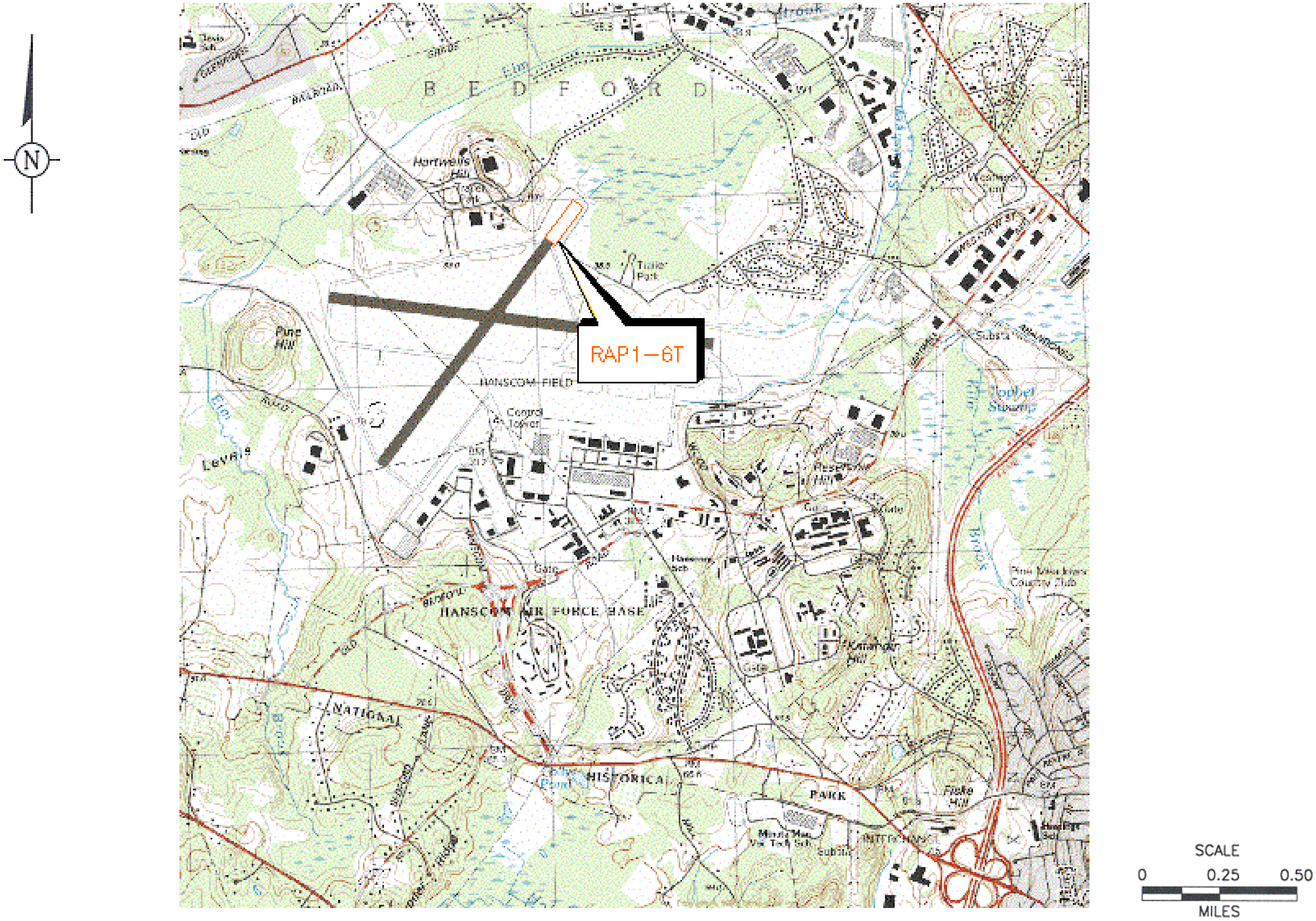


Figure 1-1. Area Map of Hanscom AFB

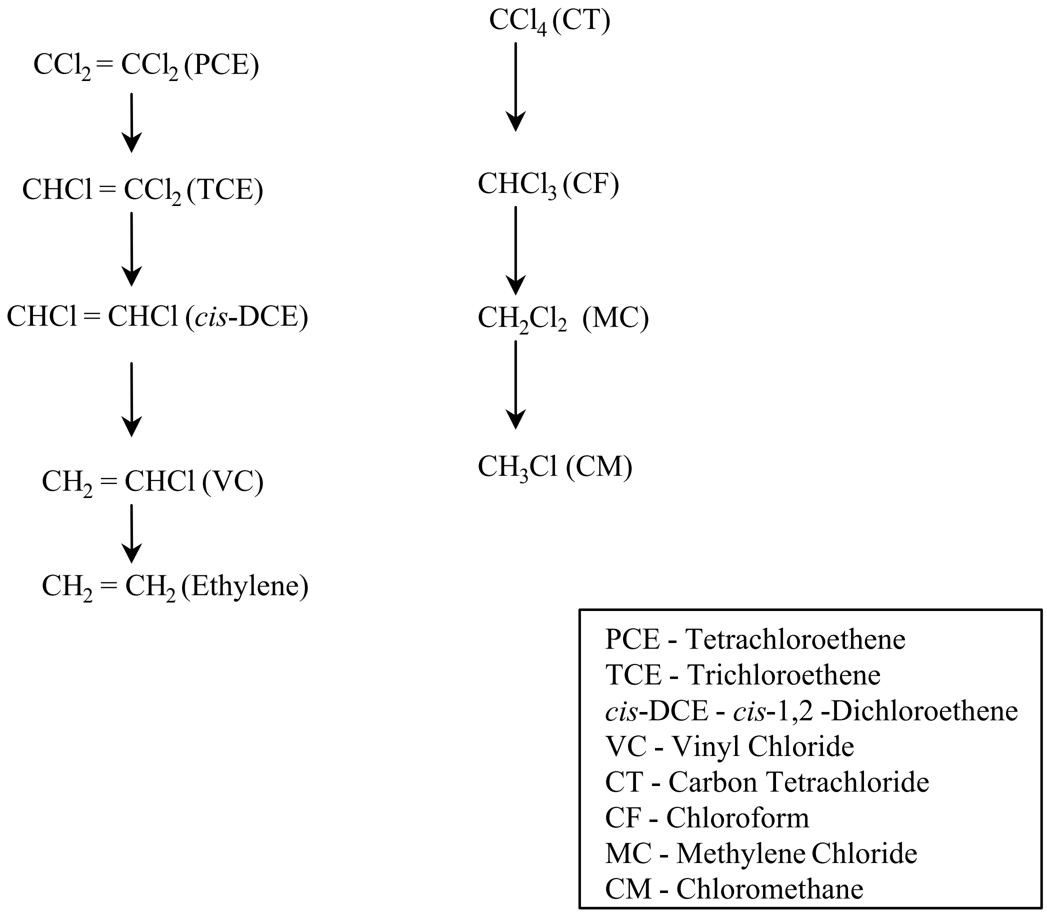


Figure 2-1. Anaerobic Transformations of Selected CAHs and their Daughter Products (after Vogel et al., 1987 and McCarty et al. 1993)

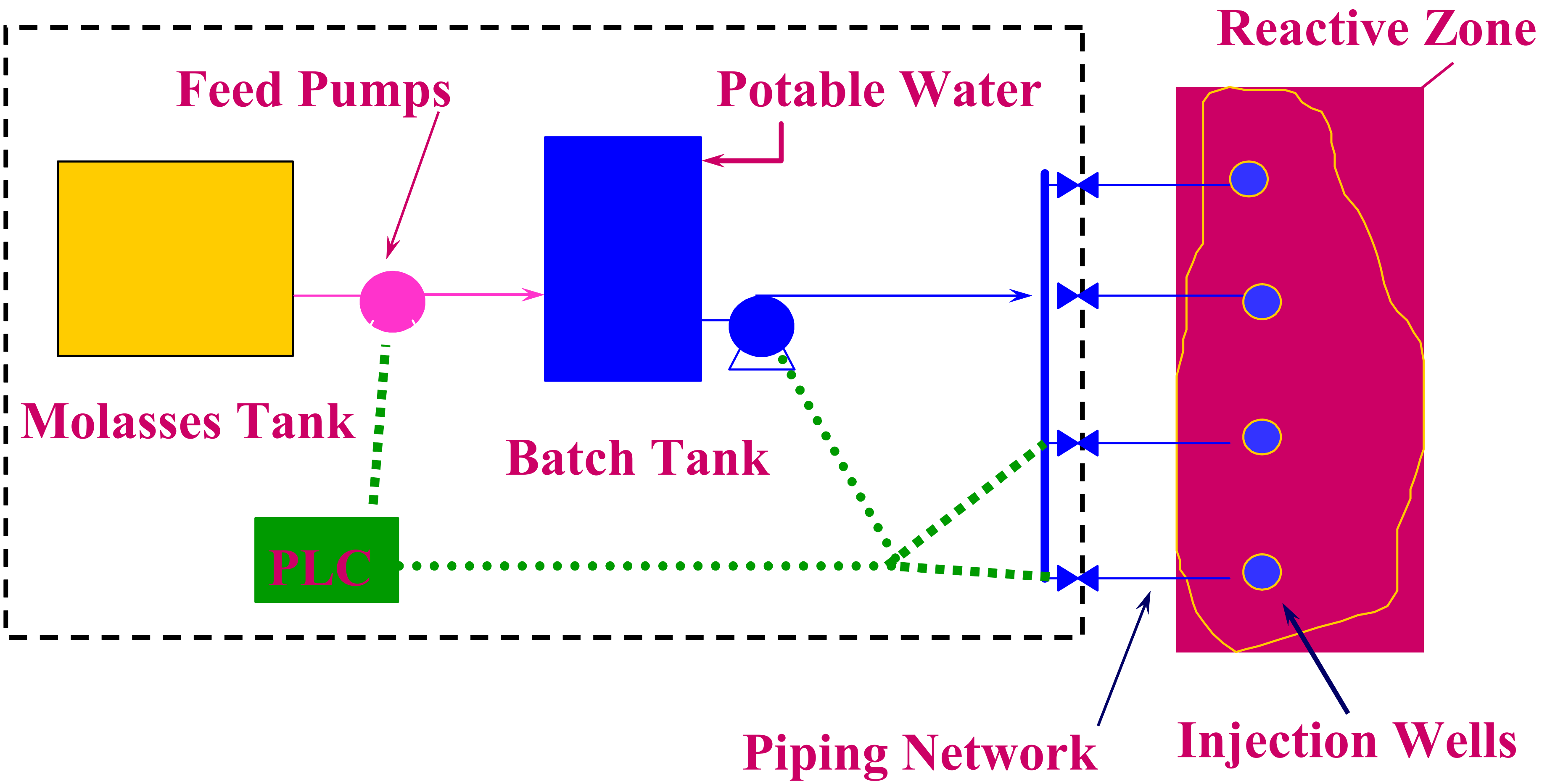
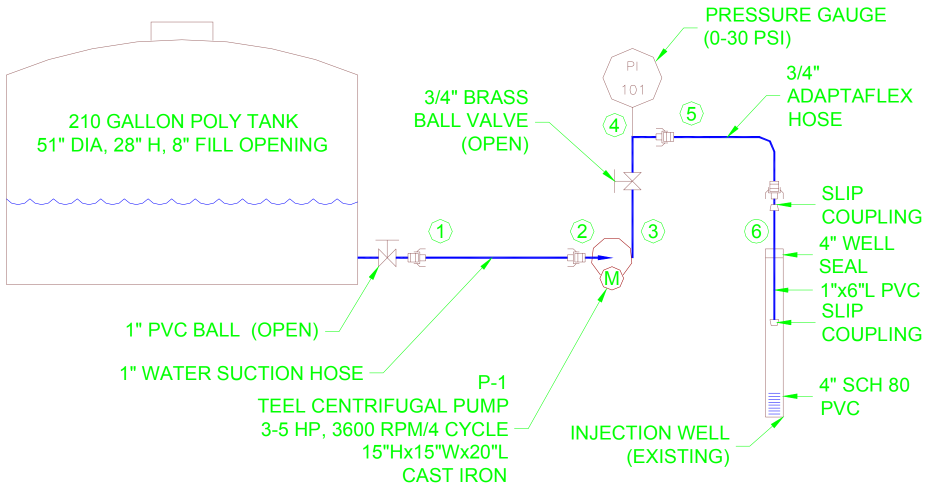


Figure 2-2. Conceptual Design for an ERD System Layout



ZONE	COMPONENT DETAILS
①	2" FPT BULKHEAD FITTING SCH 80 PVC 2"x1" FPT BUSHING SCH 80 PVC 1" CLOSE NIPPLE 1" PVC TRU-UNION BALL VALVE FPTxFPT 1" MPT POLYPROPYLENE ADAPTER, P-T COUPLING 1" I.D. GATES WATER SUCTION HOSE, 10 FT, 125# POLYPROPYLENE (1" COUPLER HOSE SHANK @ EITHER END OF HOSE)
②	1" MPT POLYPROPYLENE ADAPTER, PT COUPLING 1"x1-1/2" FPT BLACK REDUCER BUSHING
③	1-1/2"x3/4" FPT BLACK REDUCER BUSHING 3/4"x4"L STEEL NIPPLE 3/4" BLACK THREADED TEE
④	3/4"x1/4" FPT BLACK REDUCER BUSHING PRESSURE GAGE
⑤	3/4" POLYPROPYLENE COUPLER WITH MPT 3/4"x25' ADAPAFLEX HOSE (3/4" POLYPROPYLENE ADAPTER HOSE SHANK @ EITHER END OF HOSE)
⑥	POLYPROPYLENE 3/4" COUPLER W/ MPT 1" SCH 40 PVC, 6" LONG THROUGH CENTER 1" SLIPxFPT COUPLING SCH 40 (TYP. OF 2)

Figure 2-3. Reagent Mixing and Injection System Schematic

Figure 2-4. Reagent Mixing and Injection System

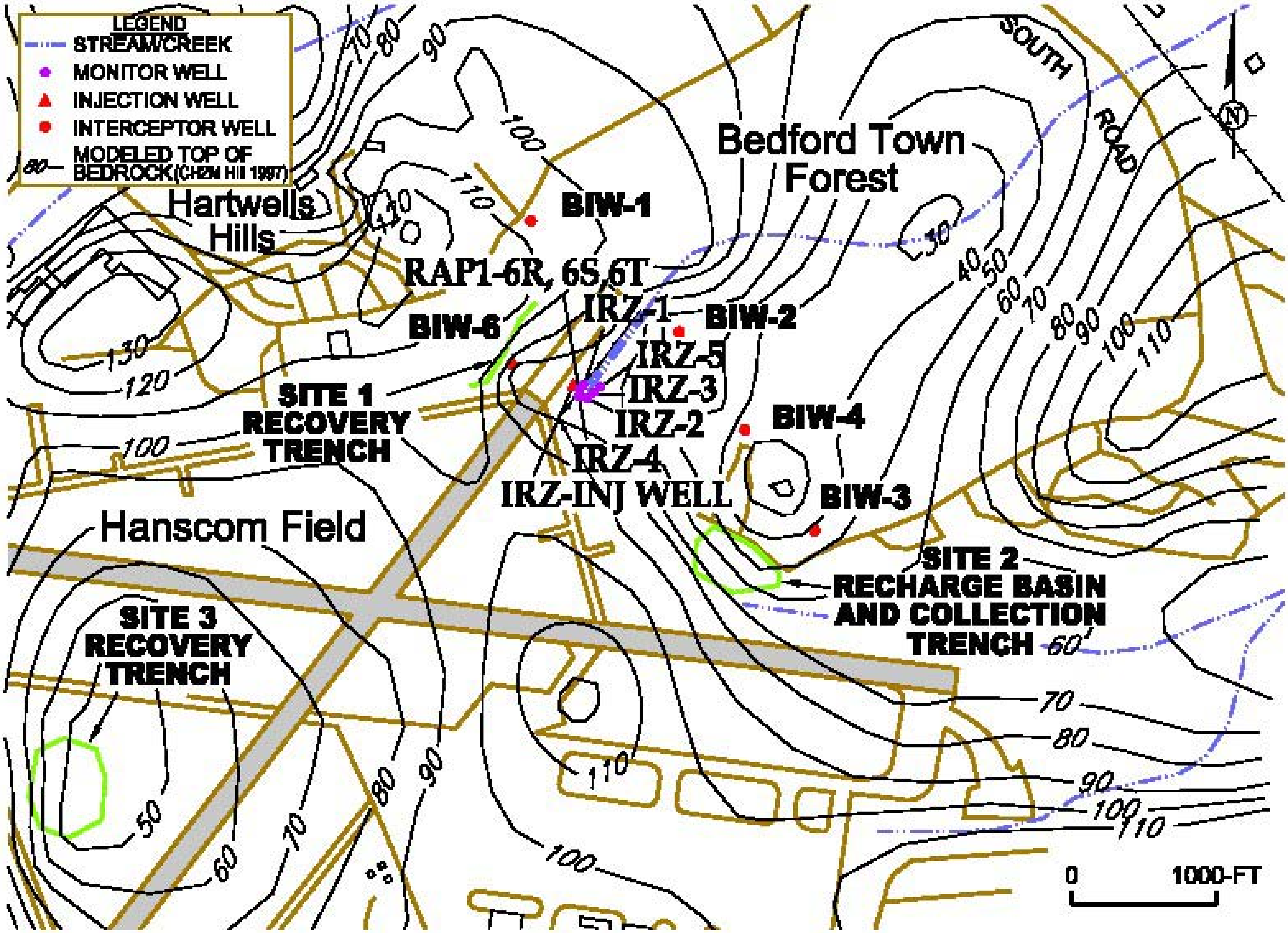
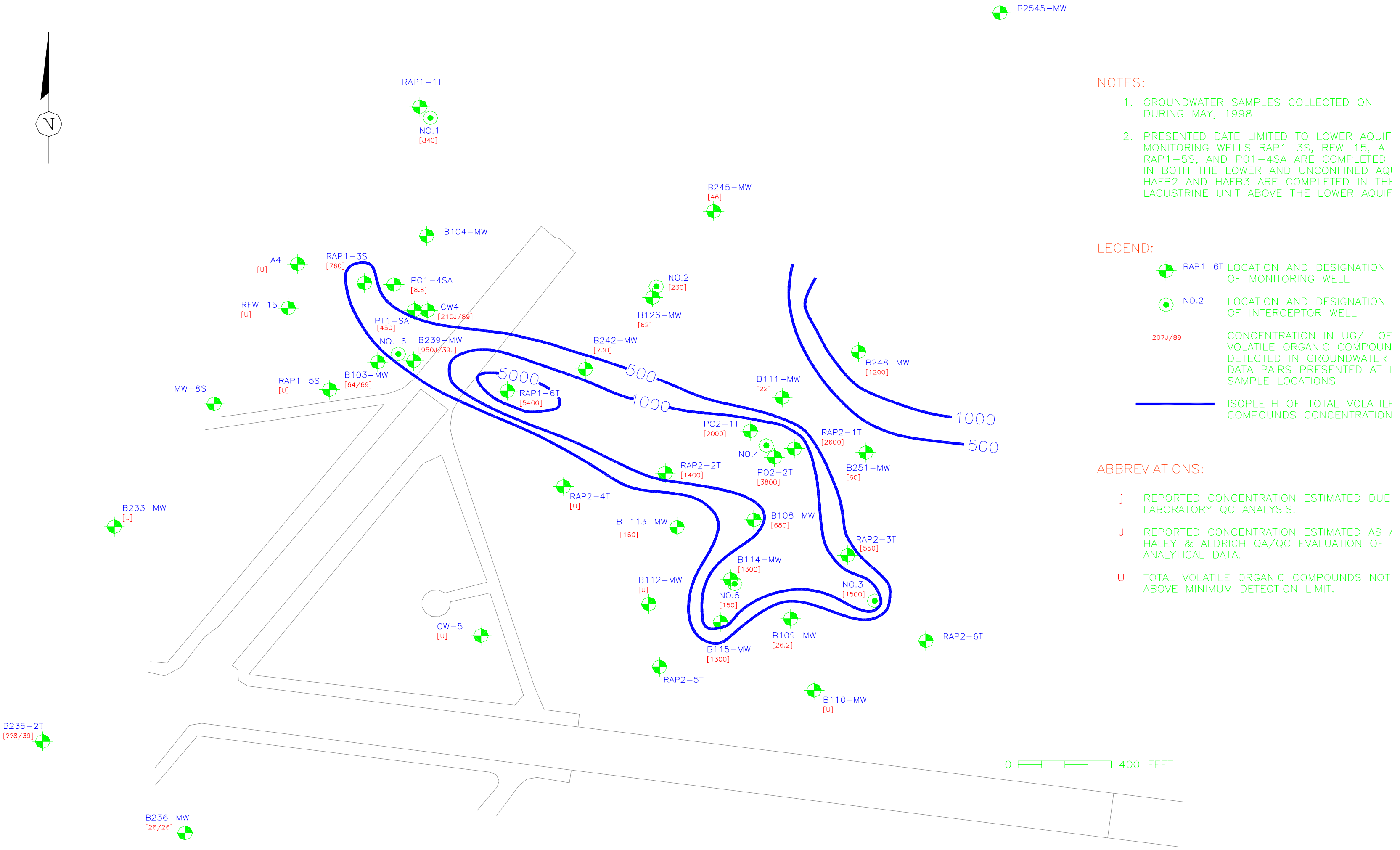


Figure 3-1. Overview of Hanscom AFB Showing Extraction Wells and Modeled Top of Bedrock Contours



NOTES:

1. GROUNDWATER SAMPLES COLLECTED ON DURING MAY, 1998.
2. PRESENTED DATE LIMITED TO LOWER AQUIF MONITORING WELLS RAP1–3S, RFW–15, A– RAP1–5S, AND P01–4SA ARE COMPLETED IN BOTH THE LOWER AND UNCONFINED AQU HAFB2 AND HAFB3 ARE COMPLETED IN THE LACUSTRINE UNIT ABOVE THE LOWER AQUIF

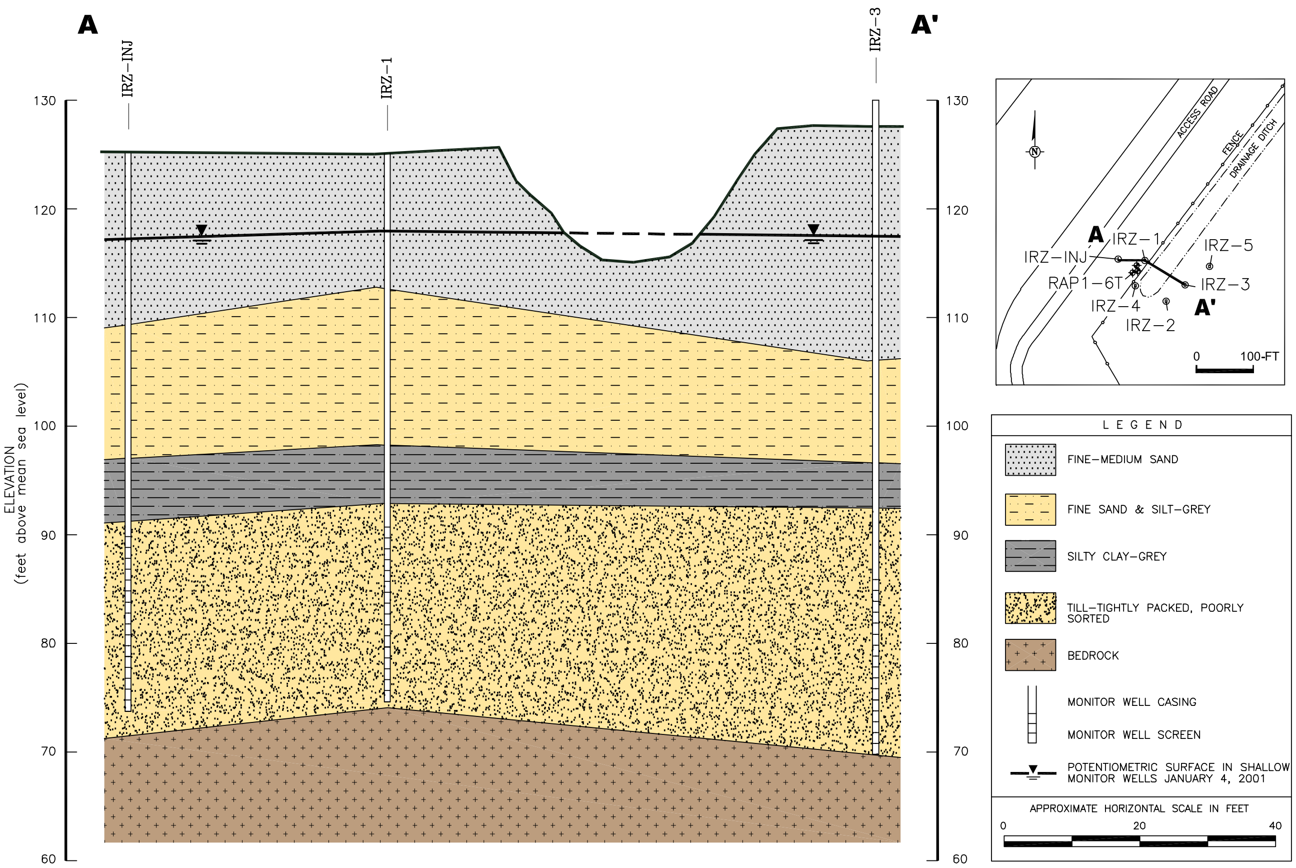
LEGEND:

⊕	RAP1–6T	LOCATION AND DESIGNATION OF MONITORING WELL
◎	NO.2	LOCATION AND DESIGNATION OF INTERCEPTOR WELL
207J/89		CONCENTRATION IN UG/L OF VOLATILE ORGANIC COMPOUN DETECTED IN GROUNDWATER DATA PAIRS PRESENTED AT SAMPLE LOCATIONS
━━		ISOPLETH OF TOTAL VOLATILE COMPOUNDS CONCENTRATION

ABBREVIATIONS:

j	REPORTED CONCENTRATION ESTIMATED DUE LABORATORY QC ANALYSIS.
J	REPORTED CONCENTRATION ESTIMATED AS HALEY & ALDRICH QA/QC EVALUATION OF ANALYTICAL DATA.
U	TOTAL VOLATILE ORGANIC COMPOUNDS NOT ABOVE MINIMUM DETECTION LIMIT.

Figure 3-2. Total VOC Concentrations in Lower Aquifer Near RAP1-6T, May 1998



ARCADIS

4915 Prospectus Drive
Suite F, DURHAM, NC 27713
Tel: 919/544-4535 Fax: 919/544-5690

CROSS SECTION OF INJECTION AREA
AFCEF A - A'

HANSCOM AFB
BEDFORD, MASSACHUSETTS

PROJECT MANAGER
C.LUTES

CHECKED BY
V. D'AMATO

DRAWN BY
A. NORTON

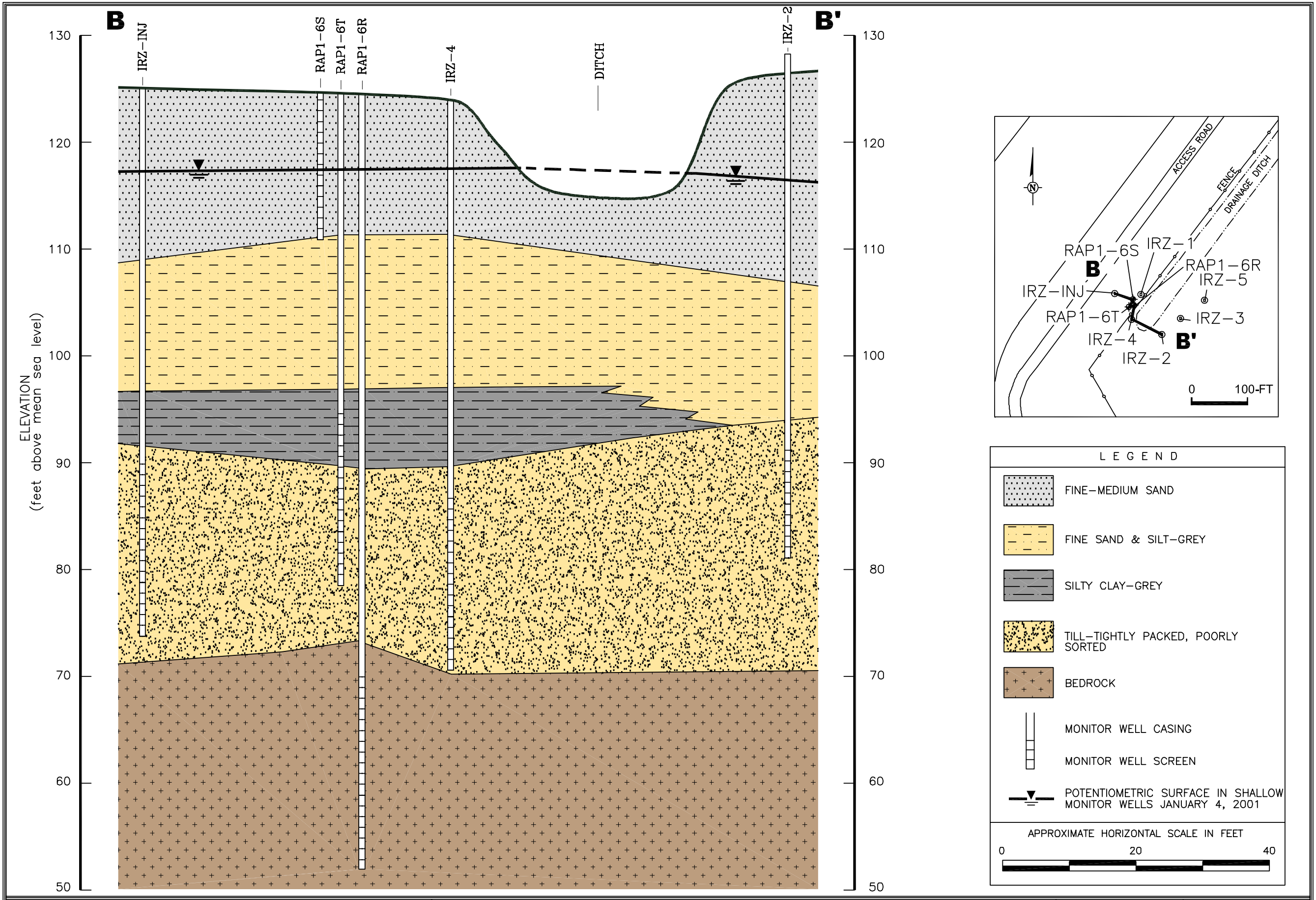
DATE DRAWN
07MAY02

DRAWING NUMBER
A–A

PROJECT NUMBER
RN009901.0012

FIGURE NUMBER

Figure 3-3. Cross Section of Injection Area, A – A'



ARCADIS

4915 Prospectus Drive
Suite F, DURHAM, NC 27713
Tel: 919/544-4535 Fax: 919/544-5690

CROSS SECTION OF INJECTION AREA
AFCEF B - B'

HANSCOM AFB
BEDFORD, MASSACHUSETTS

PROJECT MANAGER
C.LUTES

CHECKED BY
V. D'AMATO

DRAWN BY
A. NORTON

DATE DRAWN
07MAY02

DRAWING NUMBER
B-B

PROJECT NUMBER
RN009901.0012

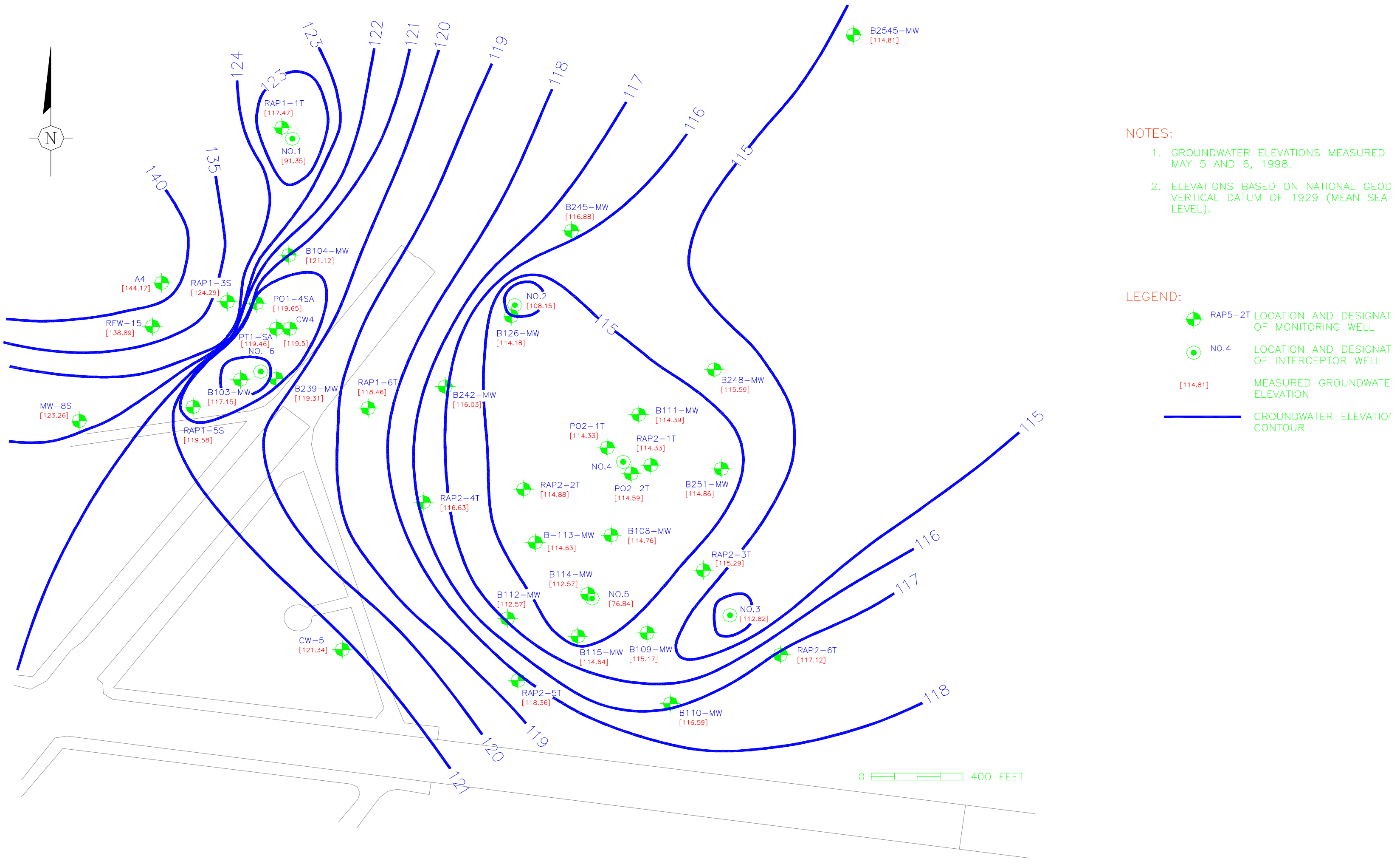
FIGURE NUMBER

Figure 3-4. Cross Section of Injection Area, B – B'

Figure 3-5. RAP1-6 Well Cluster, Viewed From Access Road Looking Southeast

Figure 3-6. Drainage Channel behind Fence and RAP1-6 Well Cluster Viewed from Southeast Side of Drainage Channel, Looking Northwest toward Overrun for Runway 23. VER Unit at Site 1 is Visible in Distant Background.

Figure 3-7. Drainage Channel Looking Northeast



NOTES:

1. GROUNDWATER ELEVATIONS MEASURED MAY 5 AND 6, 1998.
2. ELEVATIONS BASED ON NATIONAL GEOD VERTICAL DATUM OF 1929 (MEAN SEA LEVEL).

LEGEND:

RAP5–2T LOCATION AND DESIGNAT OF MONITORING WELL

NO.4 LOCATION AND DESIGNAT OF INTERCEPTOR WELL

[114.81] MEASURED GROUNDWATE ELEVATION

GROUNDWATER ELEVATIOI CONTOUR

Figure 3-8. Potentiometric Surface in Lower Aquifer Near RAP1-6T, May 1998

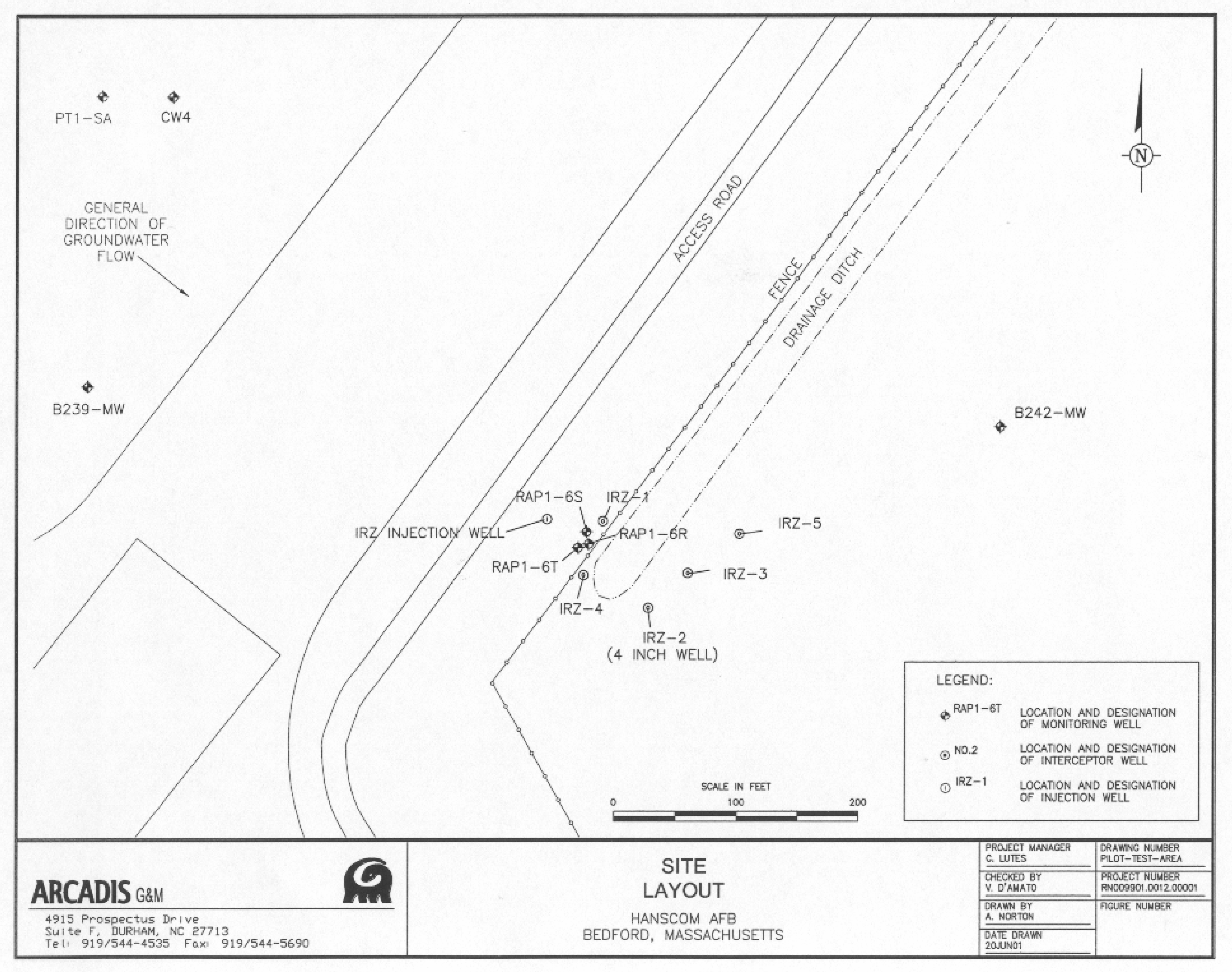


Figure 3-9. Hanscom AFB Site Layout, Pilot Test Area

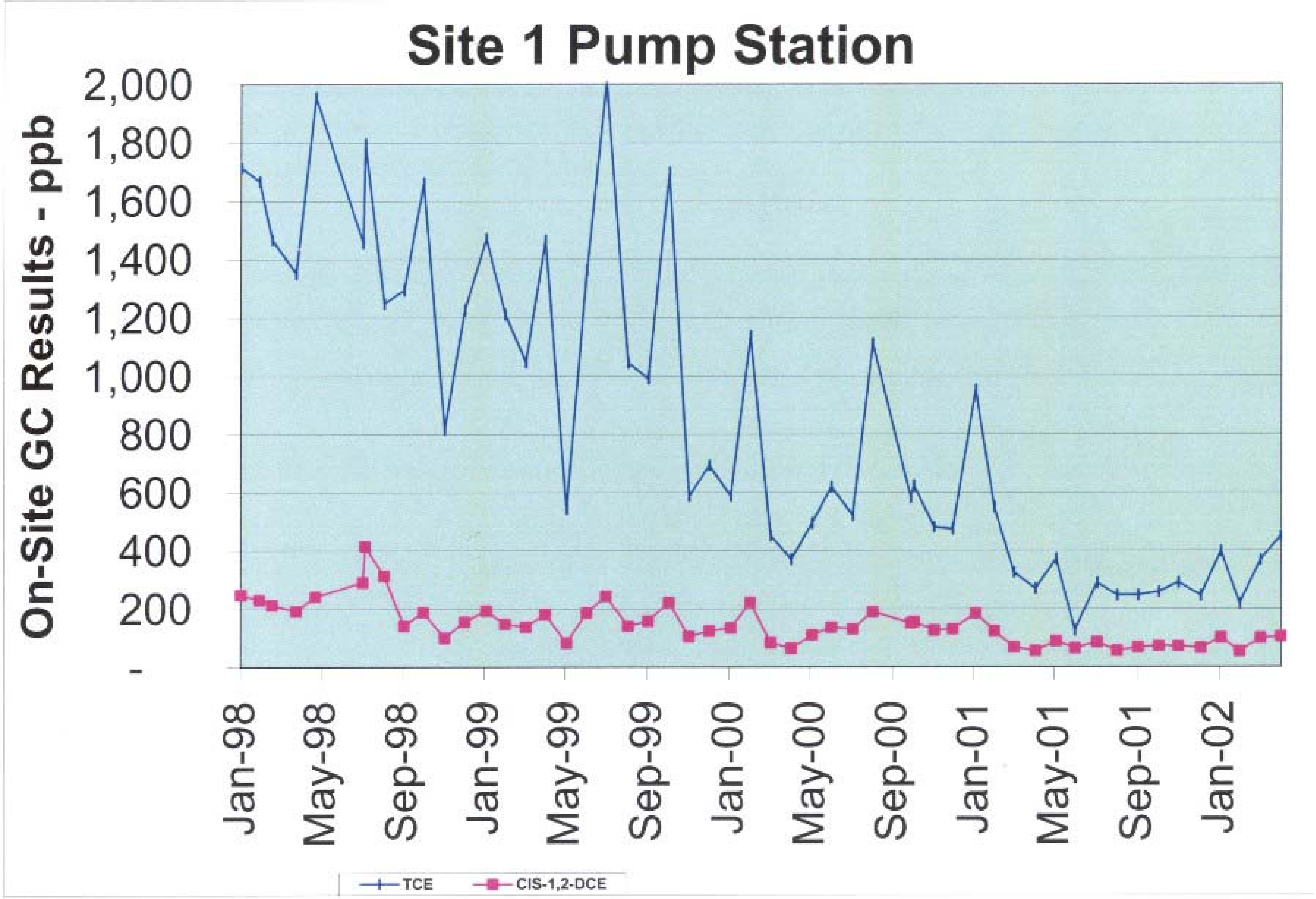


Figure 3-10. CAHs at Site 1 Pump Station (from Hanscom AFB, 2002)

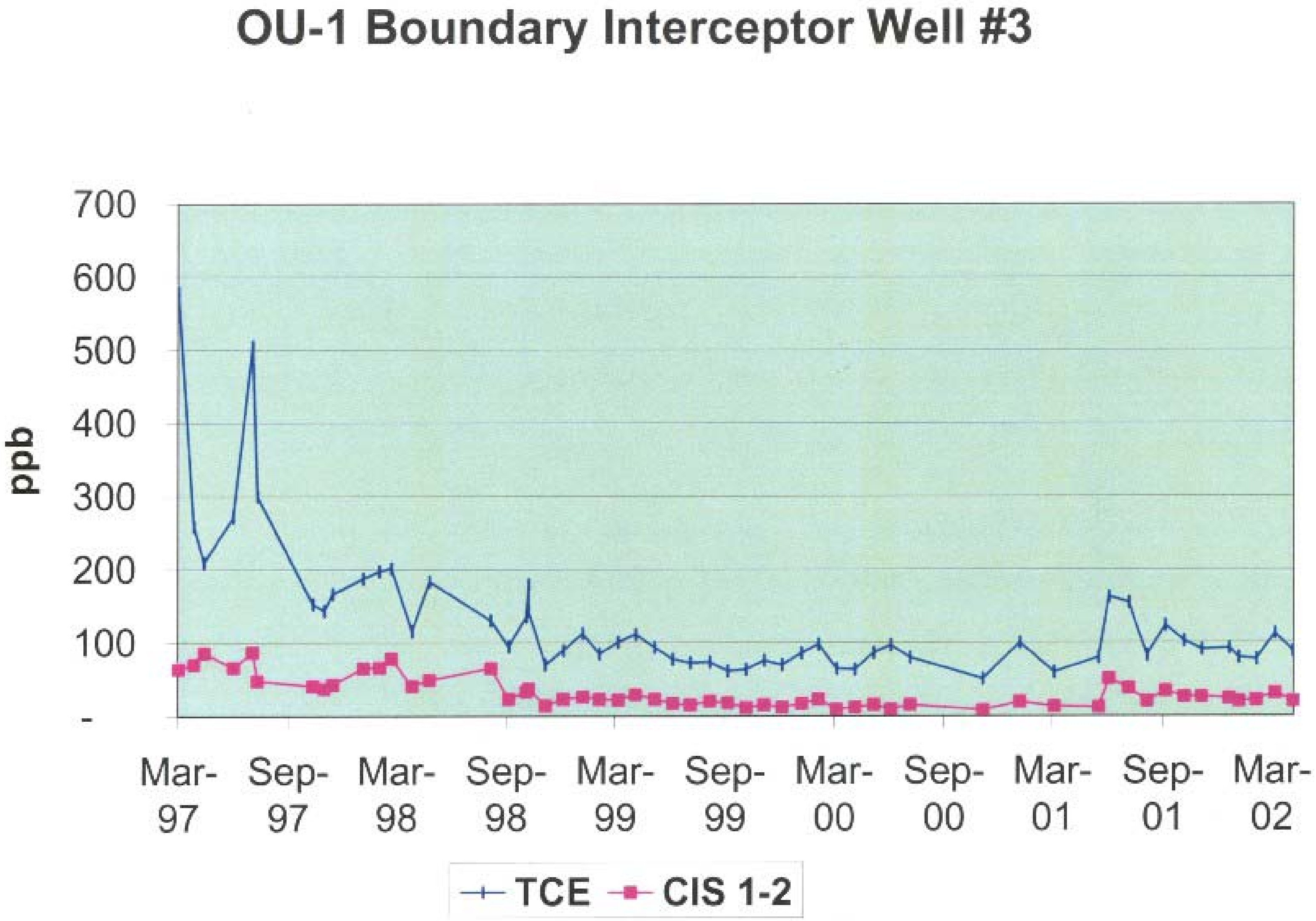
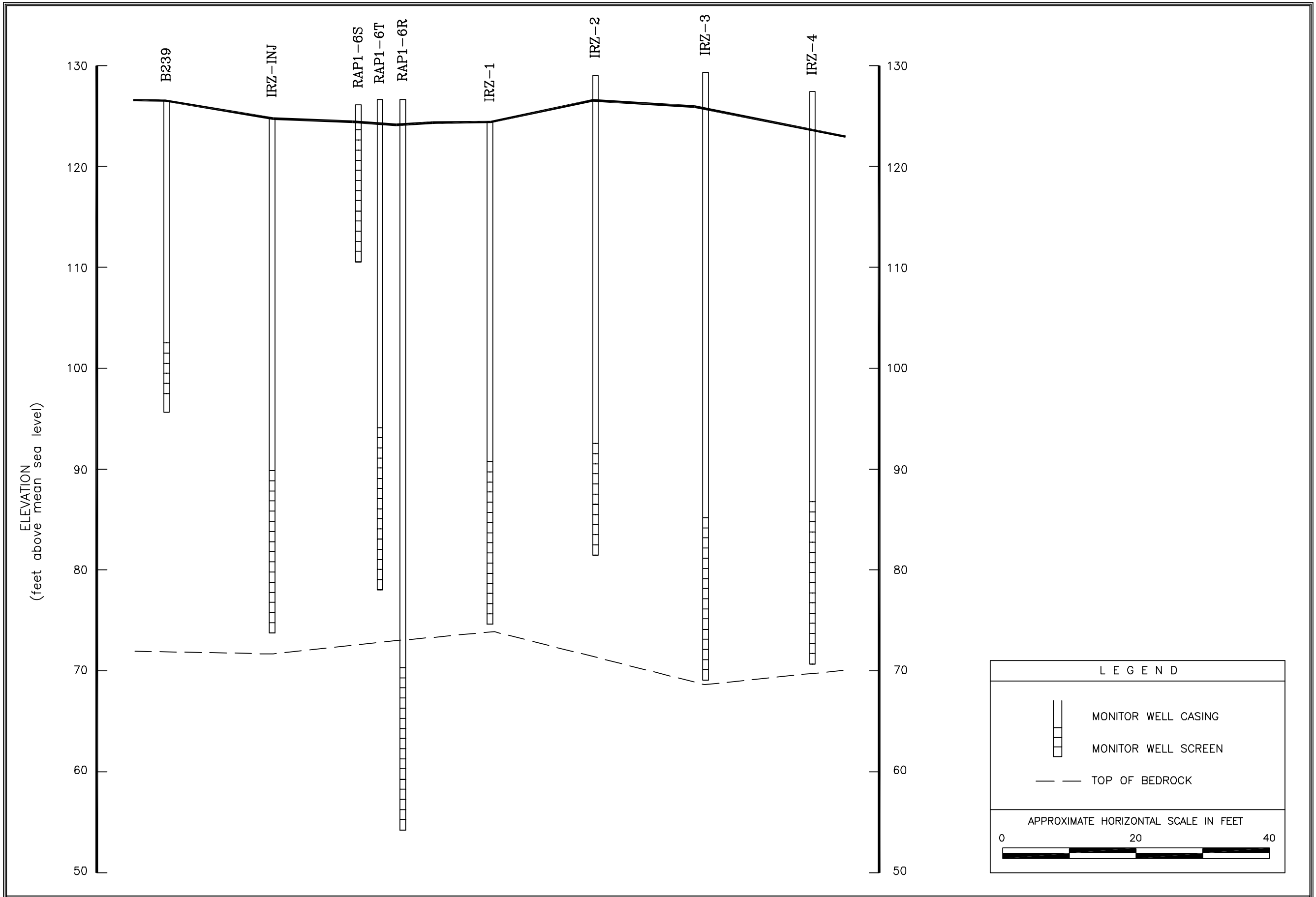


Figure 3-11. CAHs at Interceptor Well #3 (from Hanscom AFB, 2002)



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4915 Prospectus Drive
Suite F, DURHAM, NC 27713
Tel: 919/544-4535 Fax: 919/544-5690

VERTICAL CORRELATION
OF WELLS

HANSCOM AFB
BEDFORD, MASSACHUSETTS

PROJECT MANAGER C.LUTES	DRAWING NUMBER VERT-COR
CHECKED BY V. D'AMATO	PROJECT NUMBER RN009901.0012
DRAWN BY A. NORTON	FIGURE NUMBER
DATE DRAWN 07MAY02	

Figure 3-12. Vertical Correlation of Wells

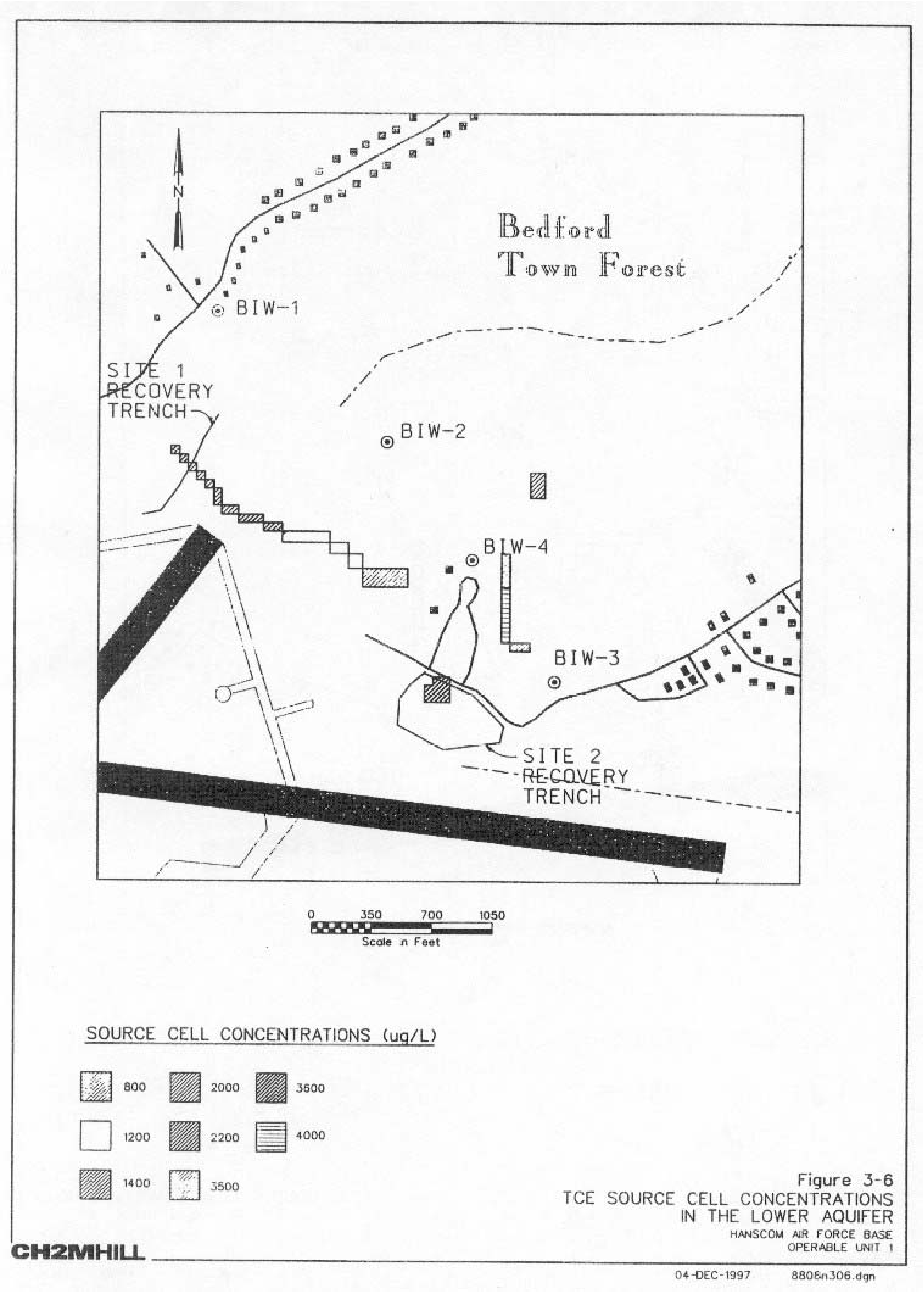
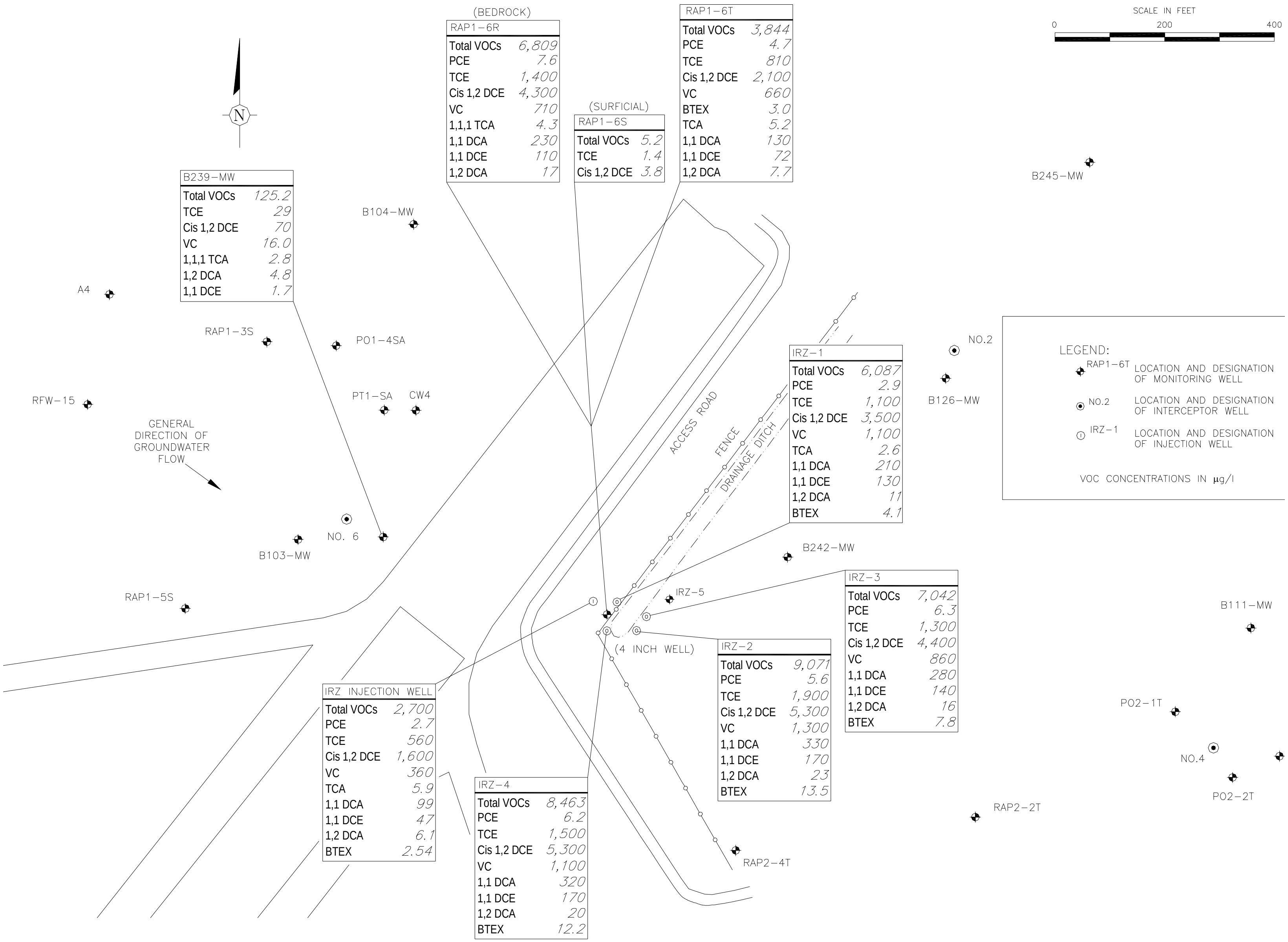


Figure 3-13. TCE Source Cell Concentrations in the Lower Aquifer



(BEDROCK)

RAP1-6R	
Total VOCs	6,809
PCE	7.6
TCE	1,400
Cis 1,2 DCE	4,300
VC	710
1,1,1 TCA	4.3
1,1 DCA	230
1,1 DCE	110
1,2 DCA	17

(SURFICIAL)

RAP1-6S	
Total VOCs	5.2
TCE	1.4
Cis 1,2 DCE	3.8

RAP1-6T	
Total VOCs	3,844
PCE	4.7
TCE	810
Cis 1,2 DCE	2,100
VC	660
BTEX	3.0
TCA	5.2
1,1 DCA	130
1,1 DCE	72
1,2 DCA	7.7

B239-MW	
Total VOCs	125.2
TCE	29
Cis 1,2 DCE	70
VC	16.0
1,1,1 TCA	2.8
1,2 DCA	4.8
1,1 DCE	1.7

IRZ-1	
Total VOCs	6,087
PCE	2.9
TCE	1,100
Cis 1,2 DCE	3,500
VC	1,100
TCA	2.6
1,1 DCA	210
1,1 DCE	130
1,2 DCA	11
BTEX	4.1

IRZ-3	
Total VOCs	7,042
PCE	6.3
TCE	1,300
Cis 1,2 DCE	4,400
VC	860
1,1 DCA	280
1,1 DCE	140
1,2 DCA	16
BTEX	7.8

IRZ-2	
Total VOCs	9,071
PCE	5.6
TCE	1,900
Cis 1,2 DCE	5,300
VC	1,300
1,1 DCA	330
1,1 DCE	170
1,2 DCA	23
BTEX	13.5

IRZ INJECTION WELL	
Total VOCs	2,700
PCE	2.7
TCE	560
Cis 1,2 DCE	1,600
VC	360
TCA	5.9
1,1 DCA	99
1,1 DCE	47
1,2 DCA	6.1
BTEX	2.54

IRZ-4	
Total VOCs	8,463
PCE	6.2
TCE	1,500
Cis 1,2 DCE	5,300
VC	1,100
1,1 DCA	320
1,1 DCE	170
1,2 DCA	20
BTEX	12.2

Figure 3-14. Summary of VOC Results for Baseline Groundwater Sampling Event – June 2000

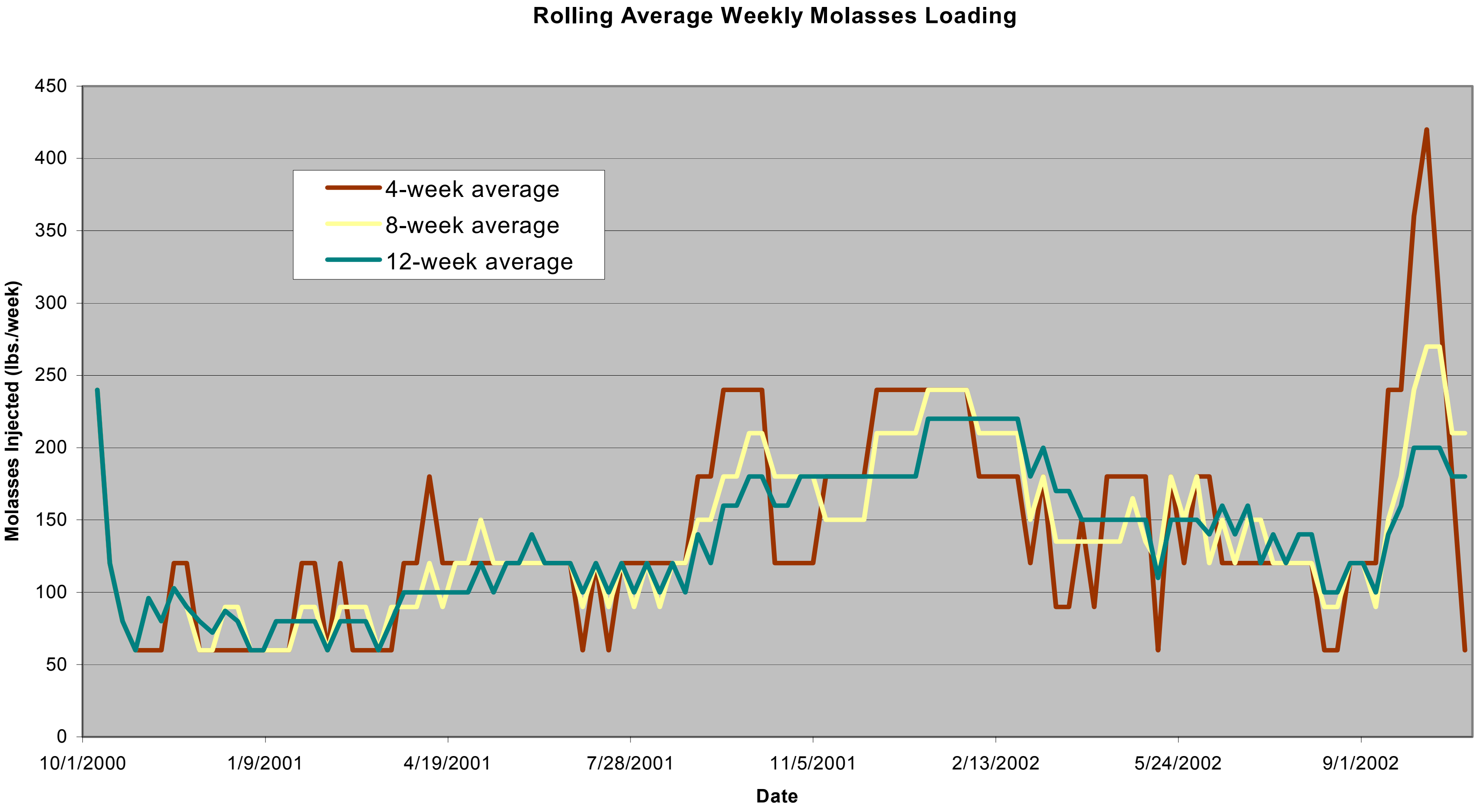
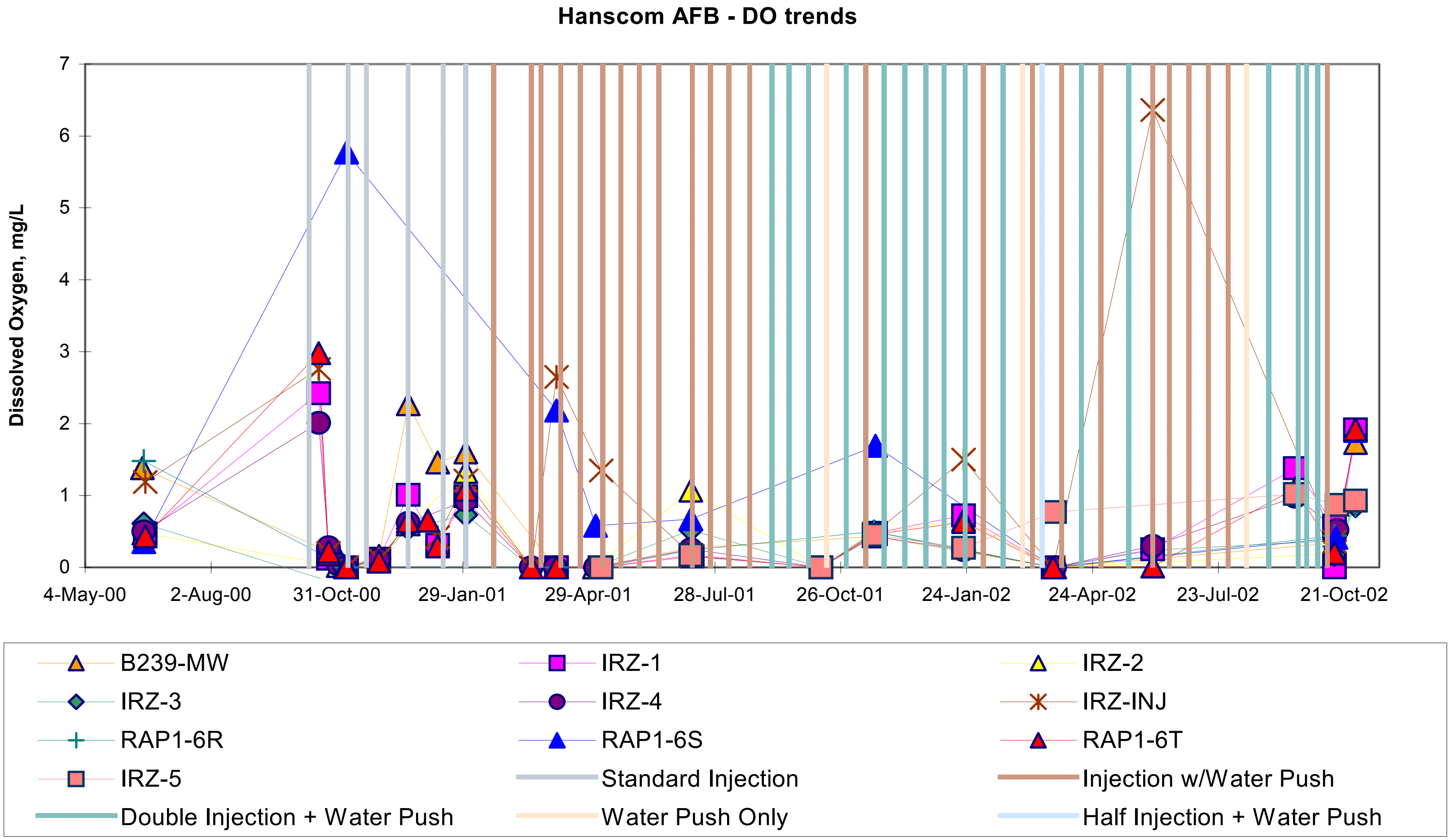
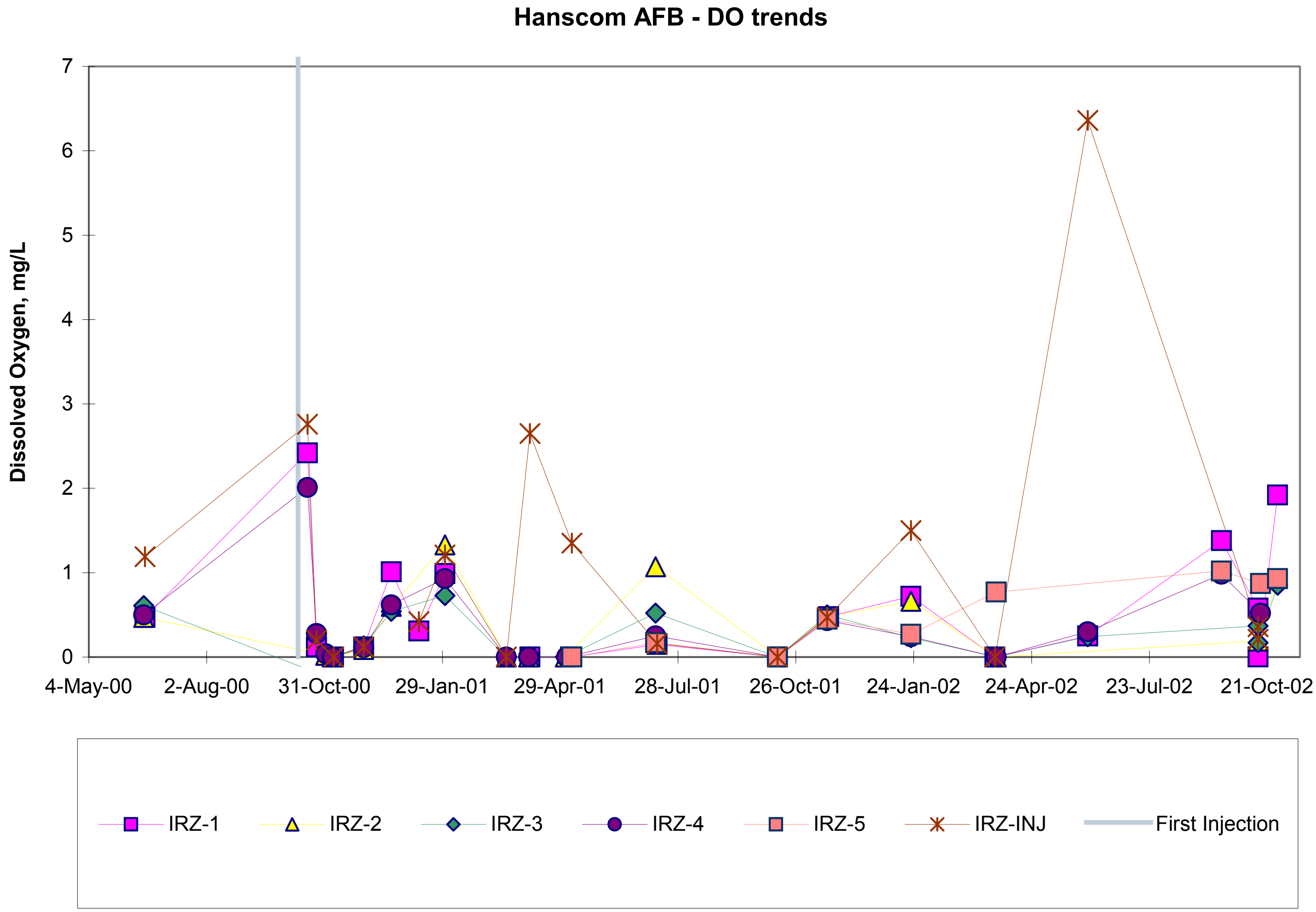


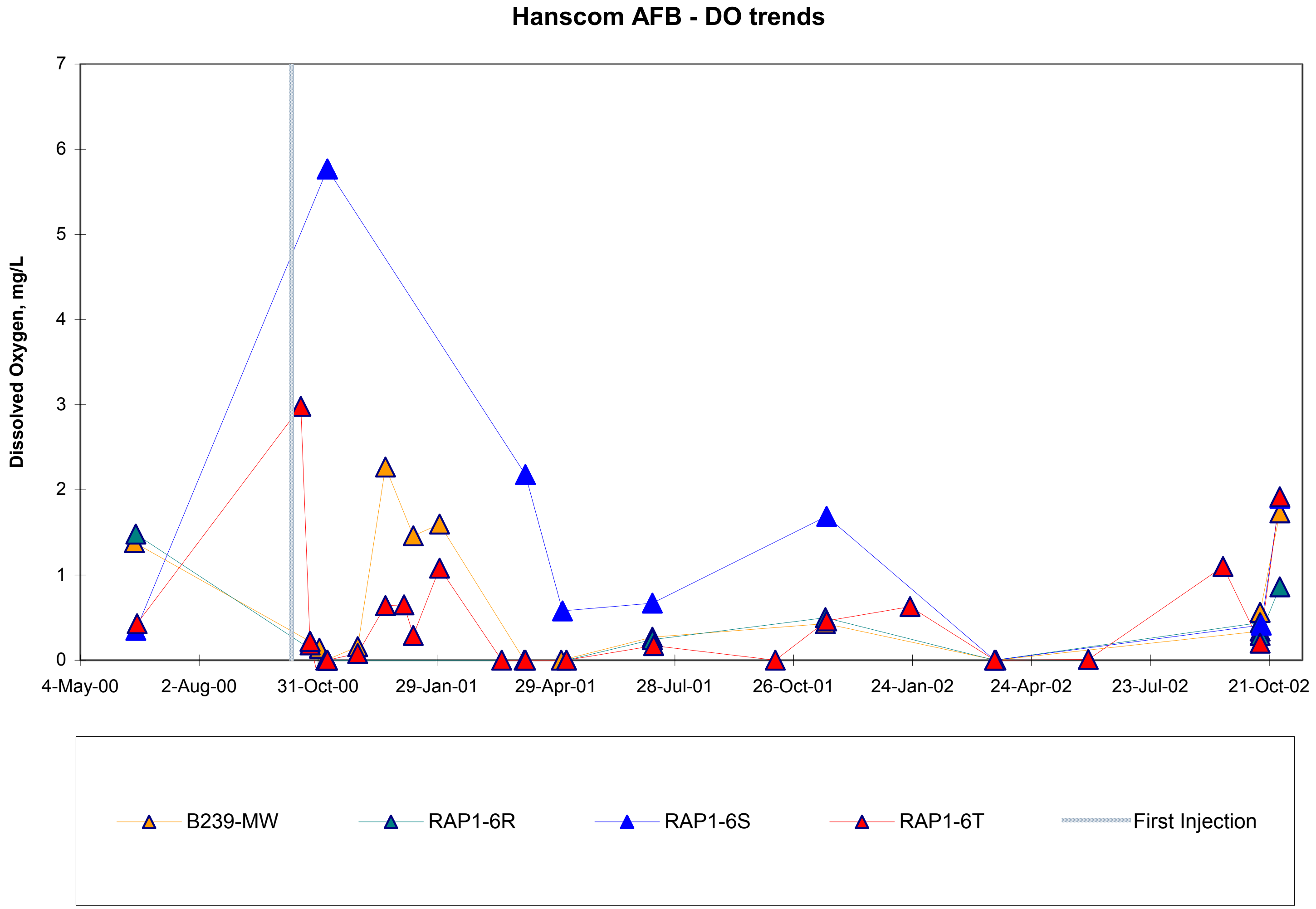
Figure 3-15. Rolling Average Weekly Molasses Loading



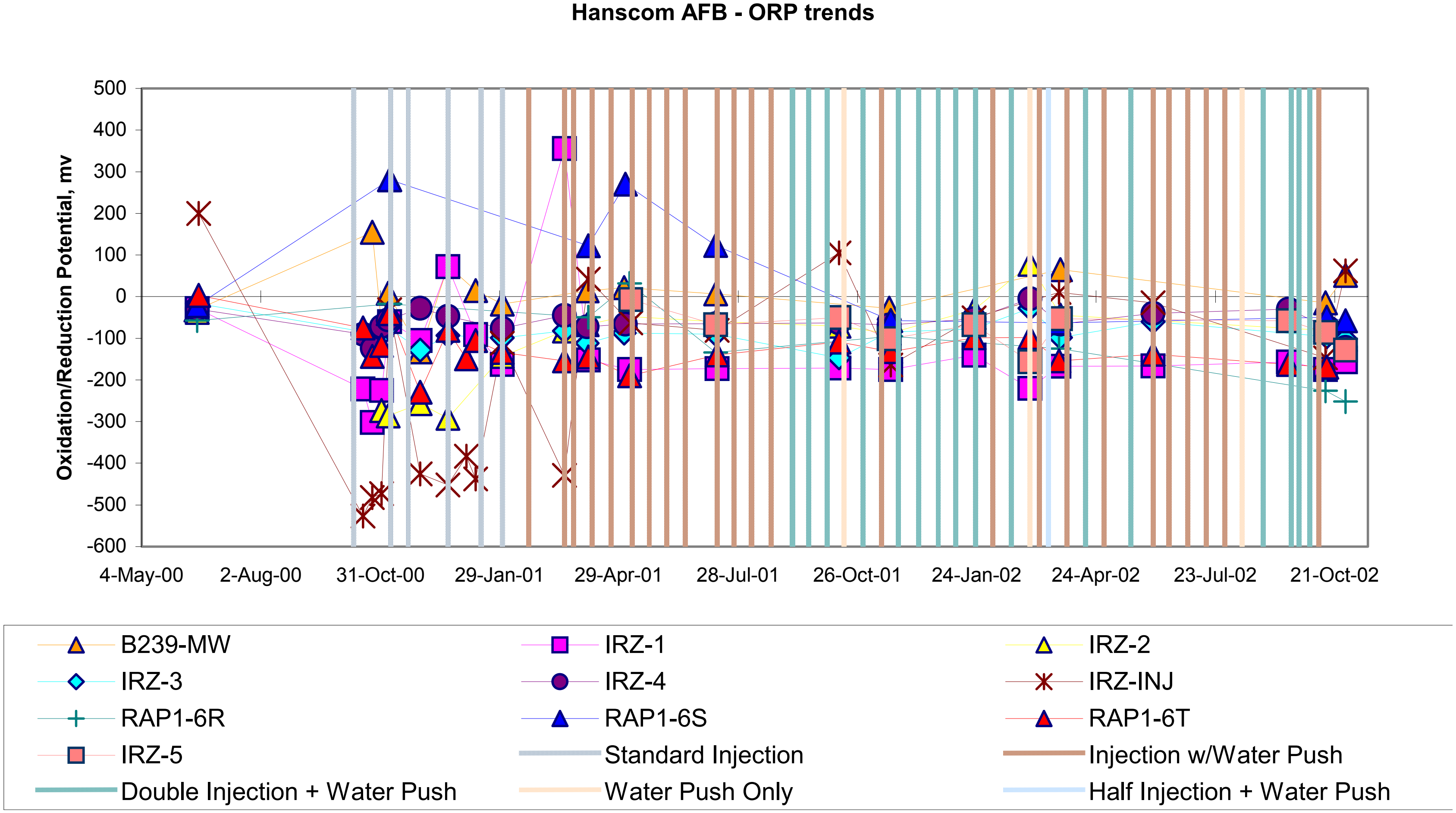
4-1-(a) Dissolved Oxygen vs. Time, All Data and Injection Events



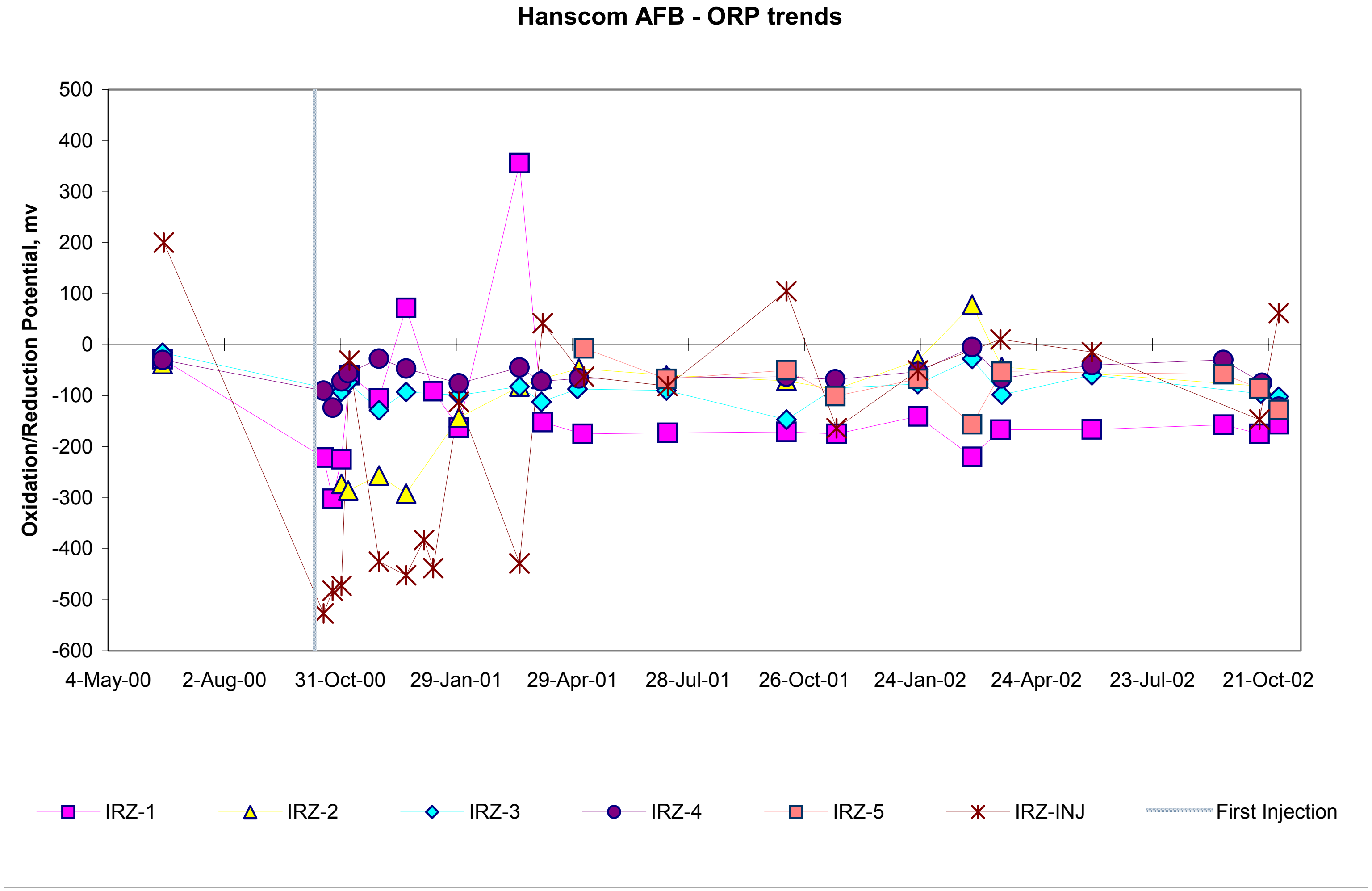
4-1-(b) Dissolved Oxygen vs. Time, "IRZ" Labeled Wells Only



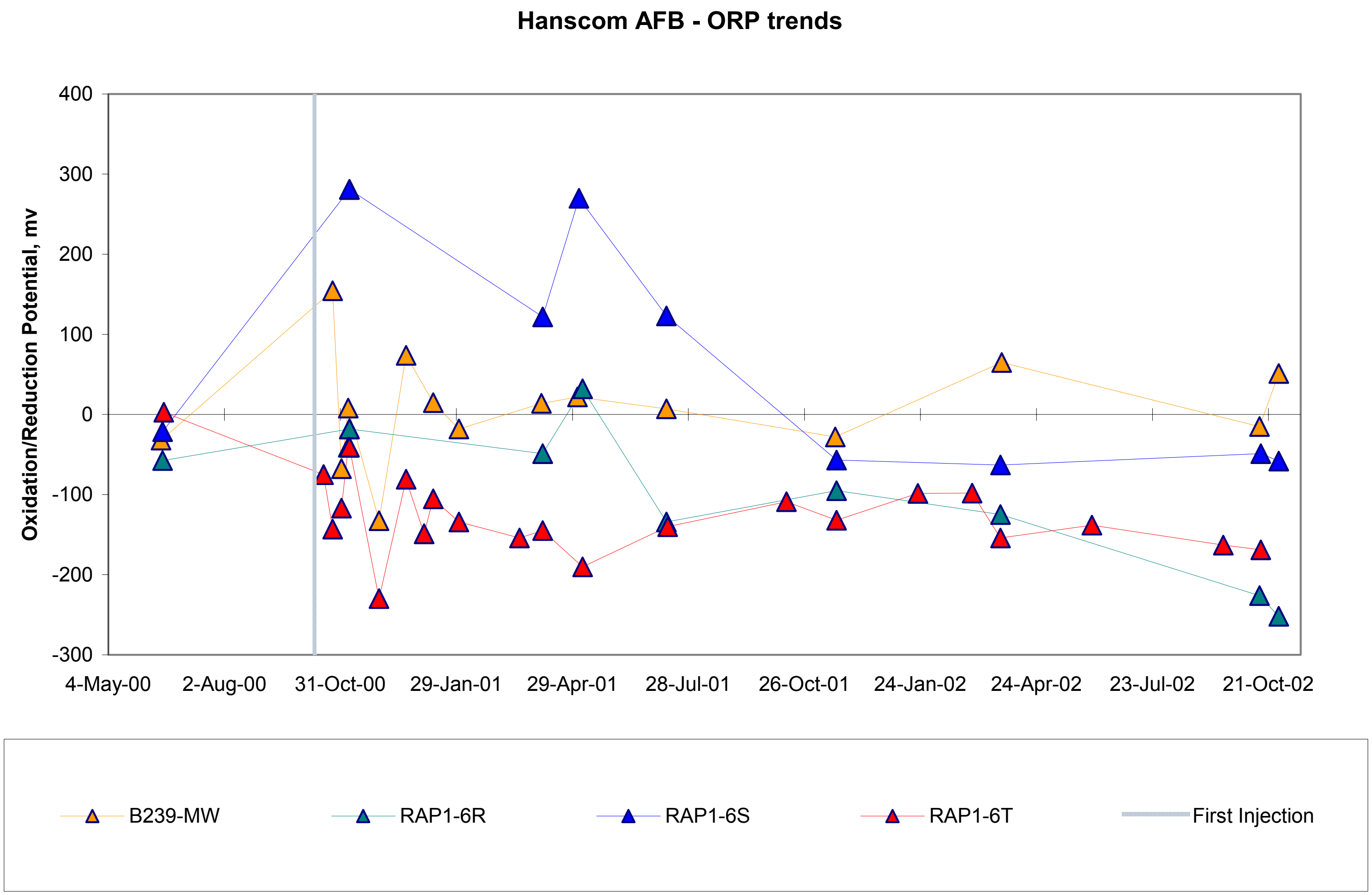
4-1-(c) Dissolved Oxygen vs. Time, "RAP and B" Labeled Wells Only



4-2-(a) Oxidation Reduction Potential vs. Time, All Data and Injection Events



4-2-(b) Oxidation Reduction Potential vs. Time, "IRZ" Labeled Wells Only



4-2-(c) Oxidation Reduction Potential vs. Time, "RAP and B" Labeled Wells Only

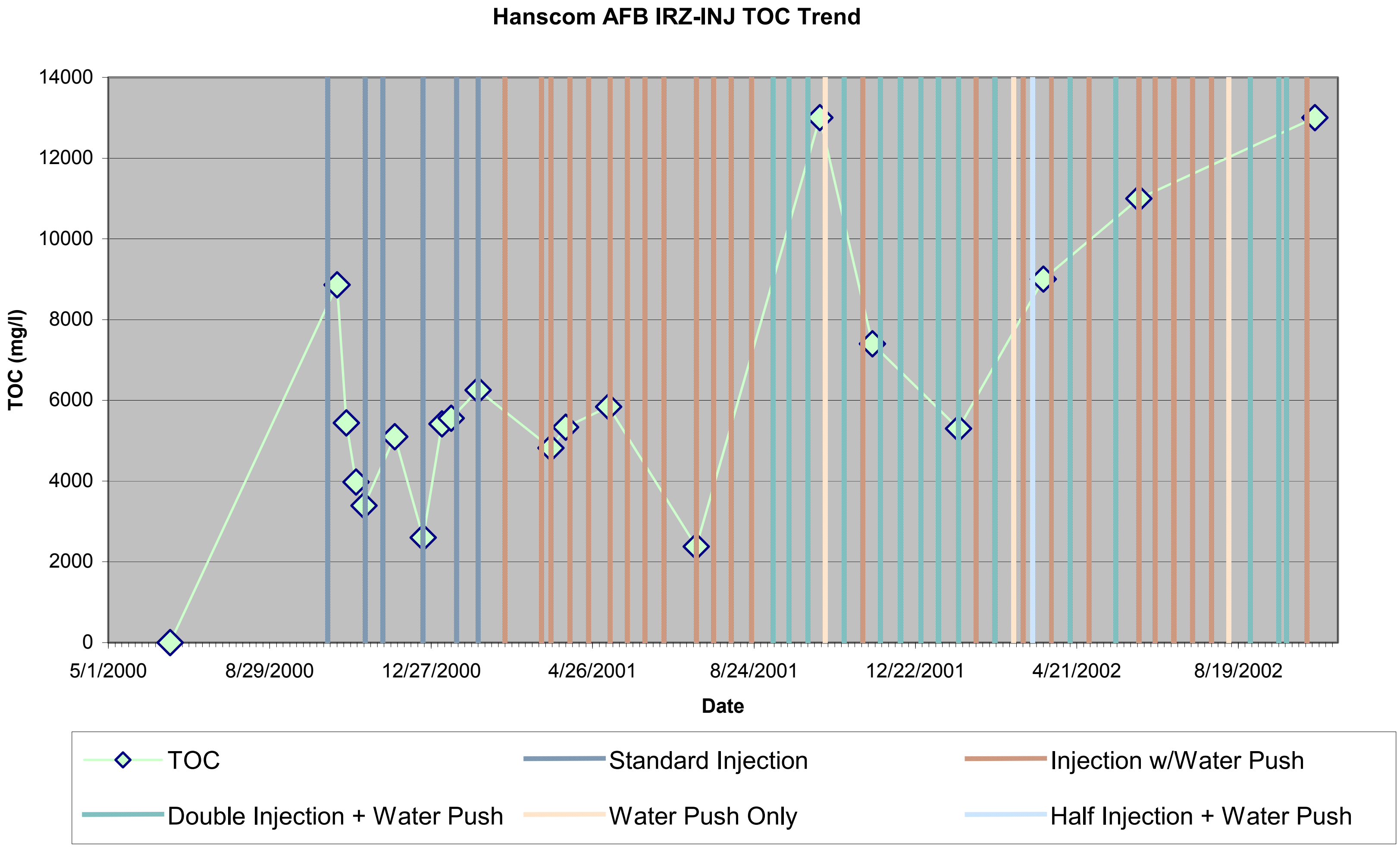
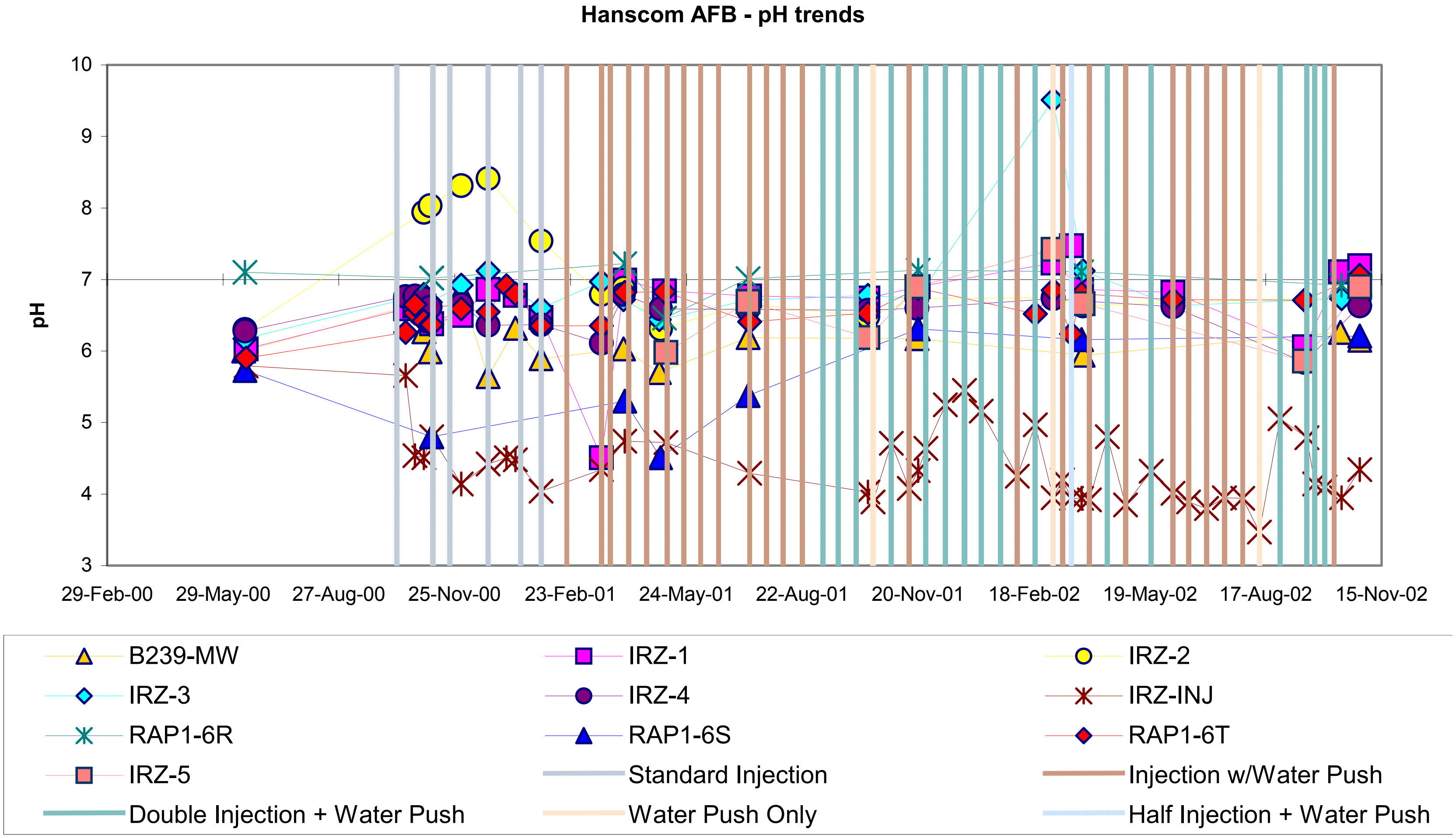
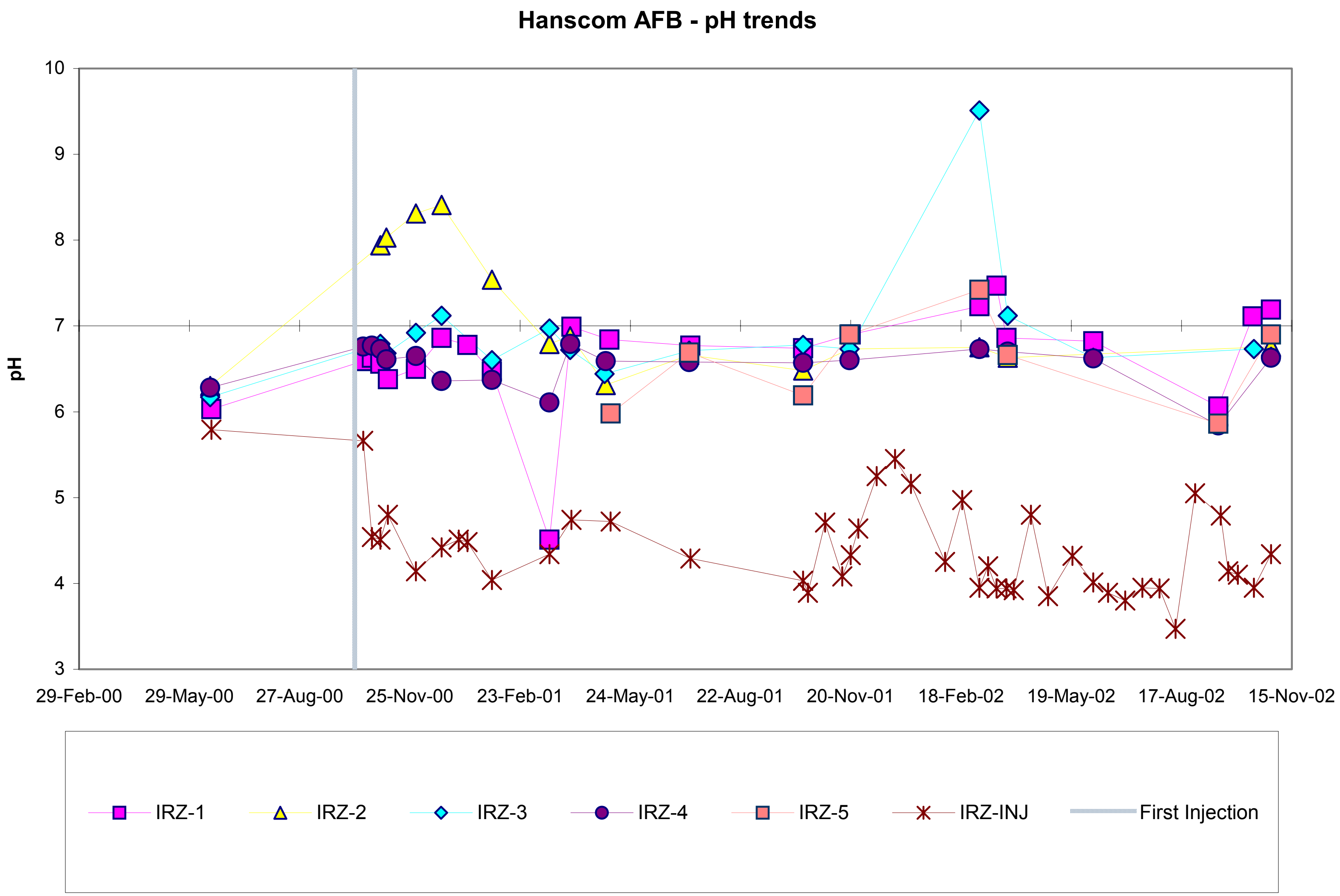


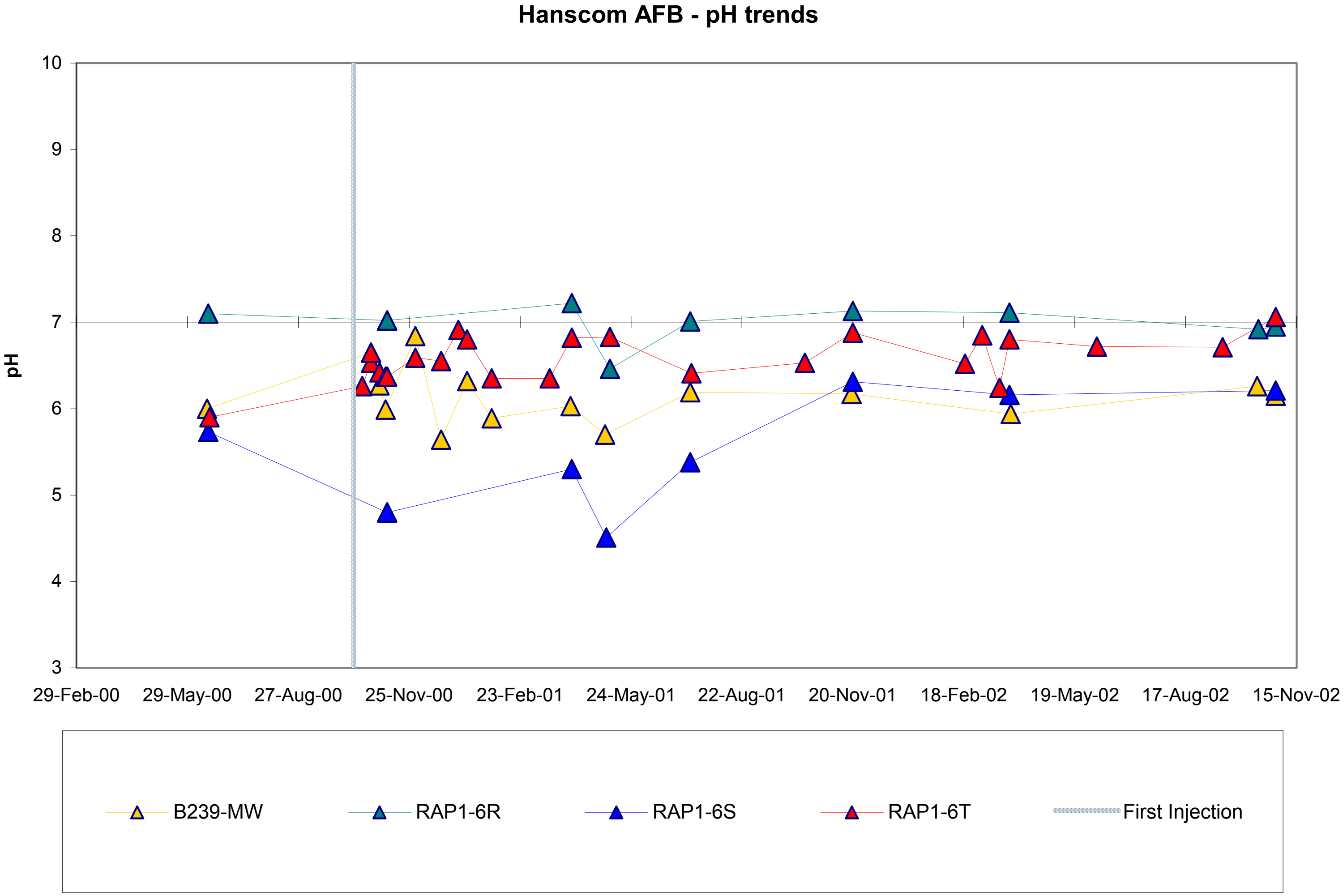
Figure 4-3. TOC Trend in the Injection Well



4-4-(a) pH vs. Time, All Data and Injection Events



4-4-(b) pH vs. Time, "IRZ" Labeled Wells Only



4-4-(c) pH vs. Time, "RAP and B" Labeled Wells Only

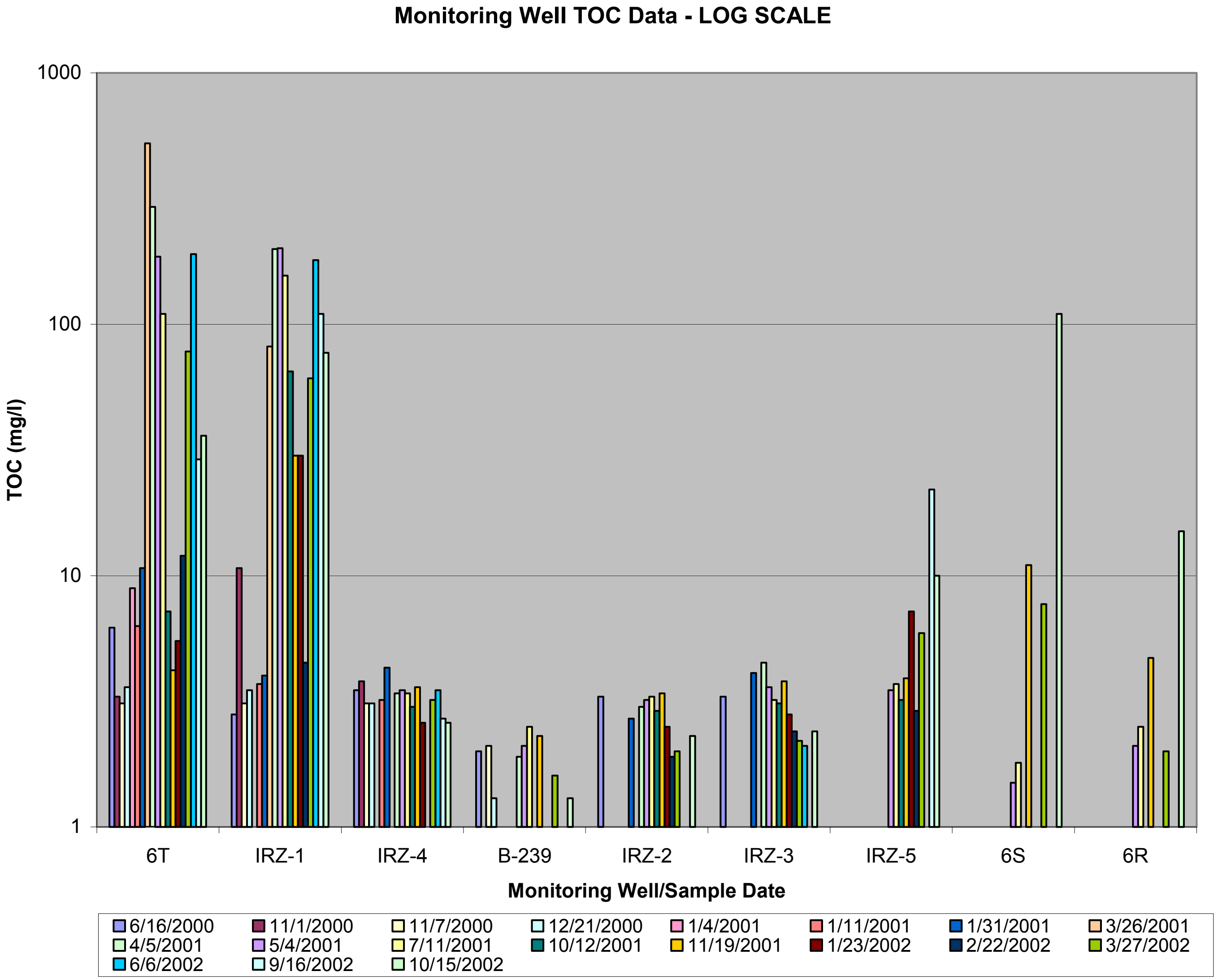


Figure 4-5. Monitoring Well TOC Data

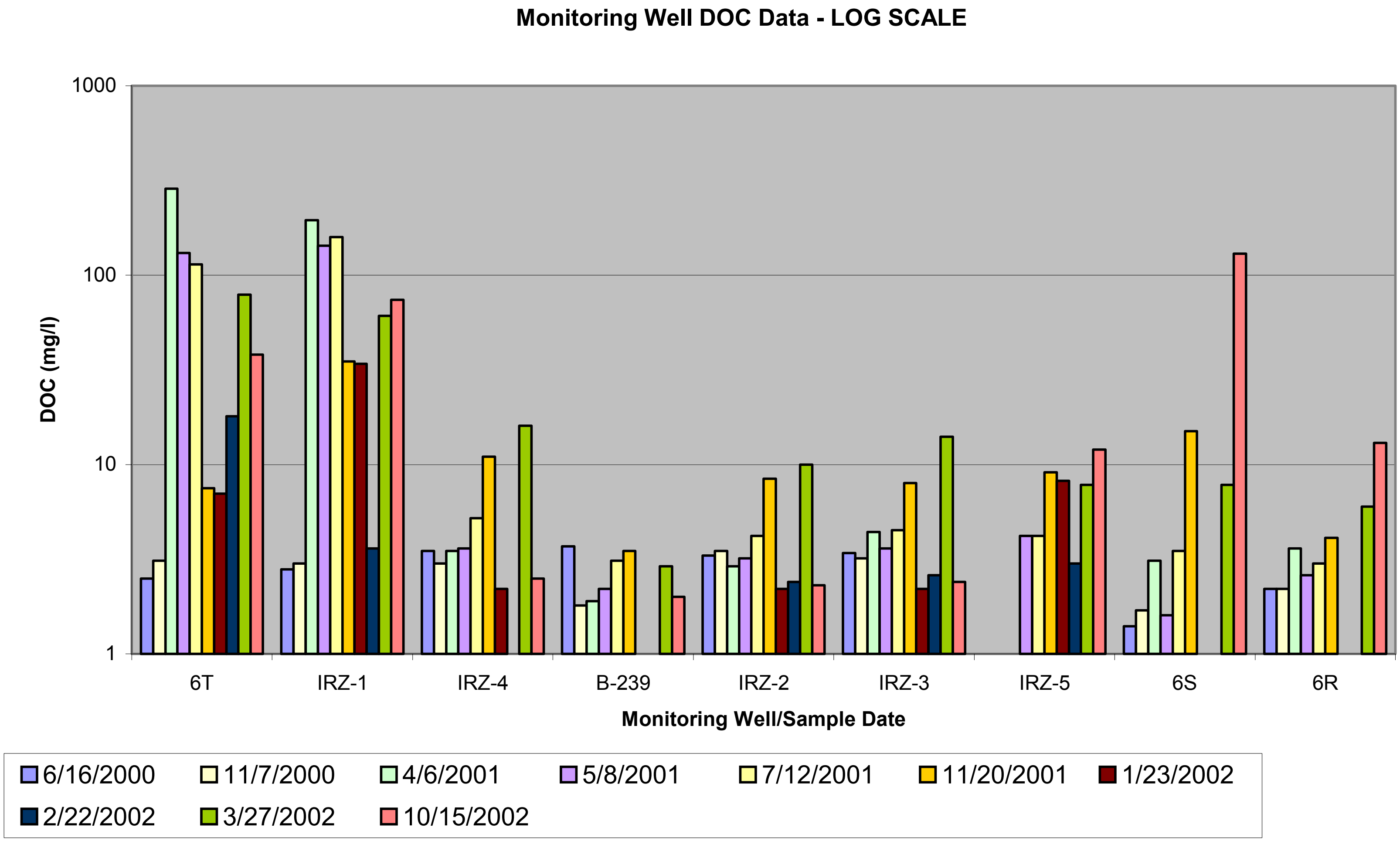


Figure 4-6. Monitoring Well DOC Data

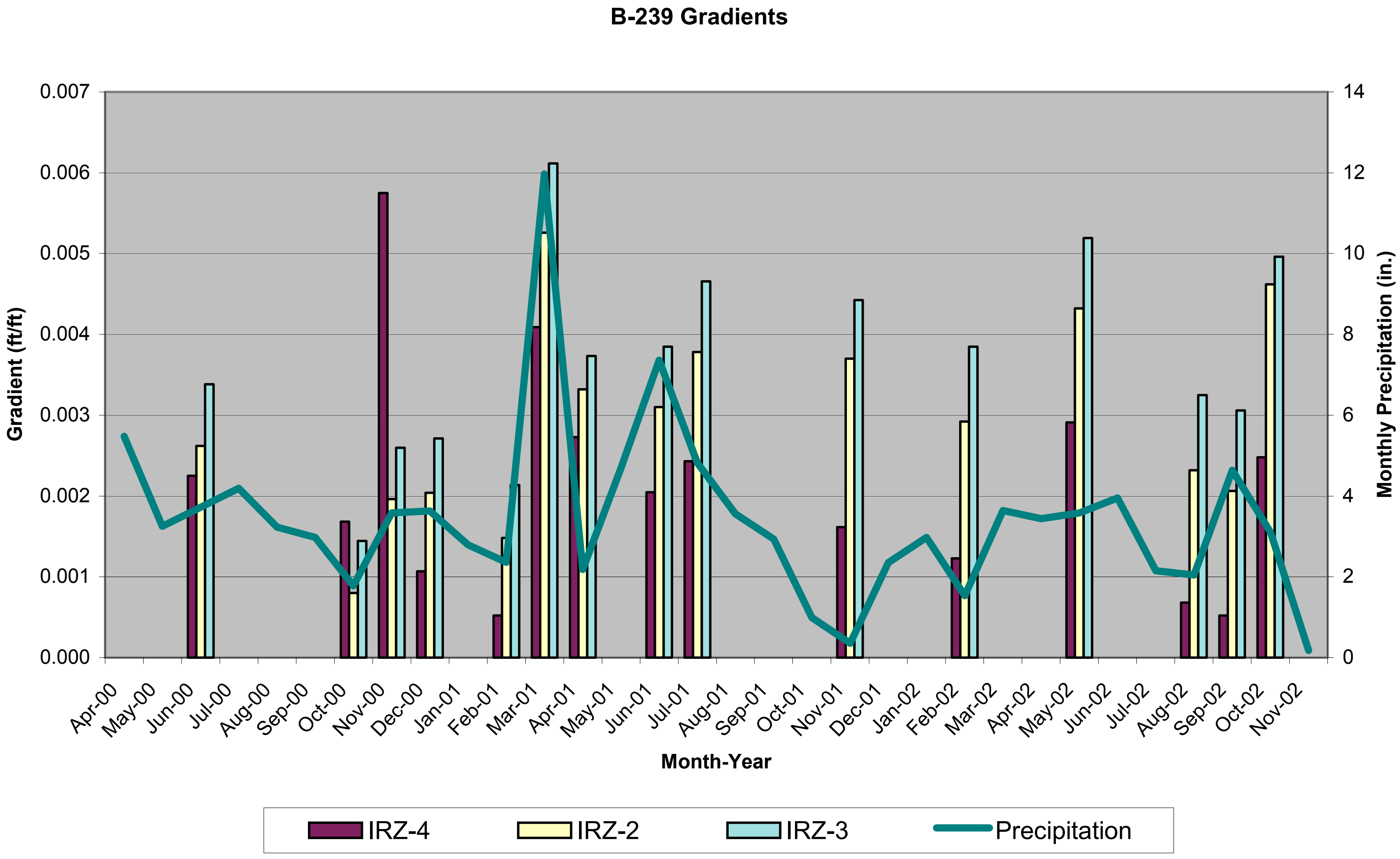


Figure 4-7. Precipitation for Bedford, MA, and Gradient Between Well B-239 and Selected Wells Over Time

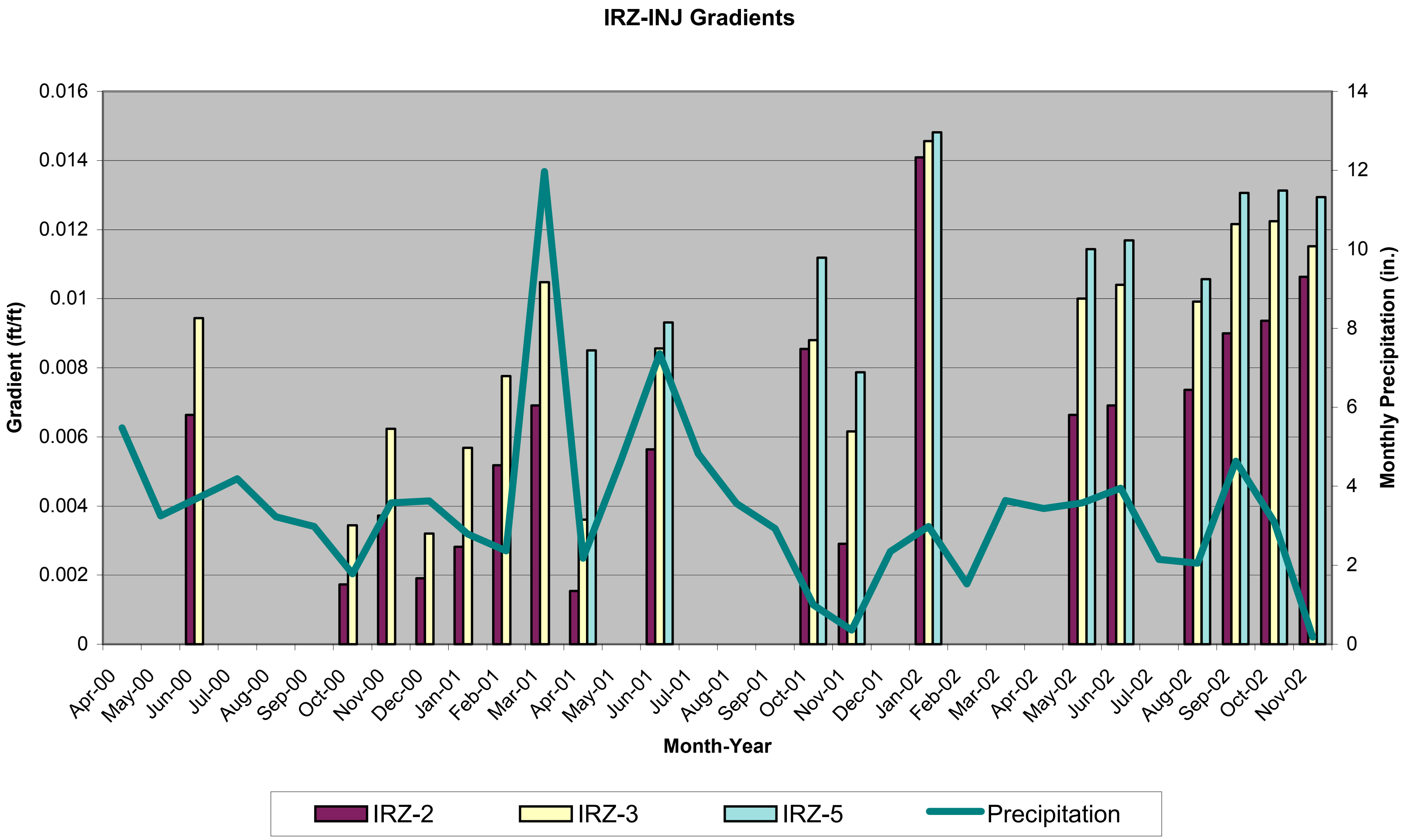


Figure 4-8. Precipitation for Bedford, MA, and Gradient Between Well IRZ-INJ and Selected Wells Over Time

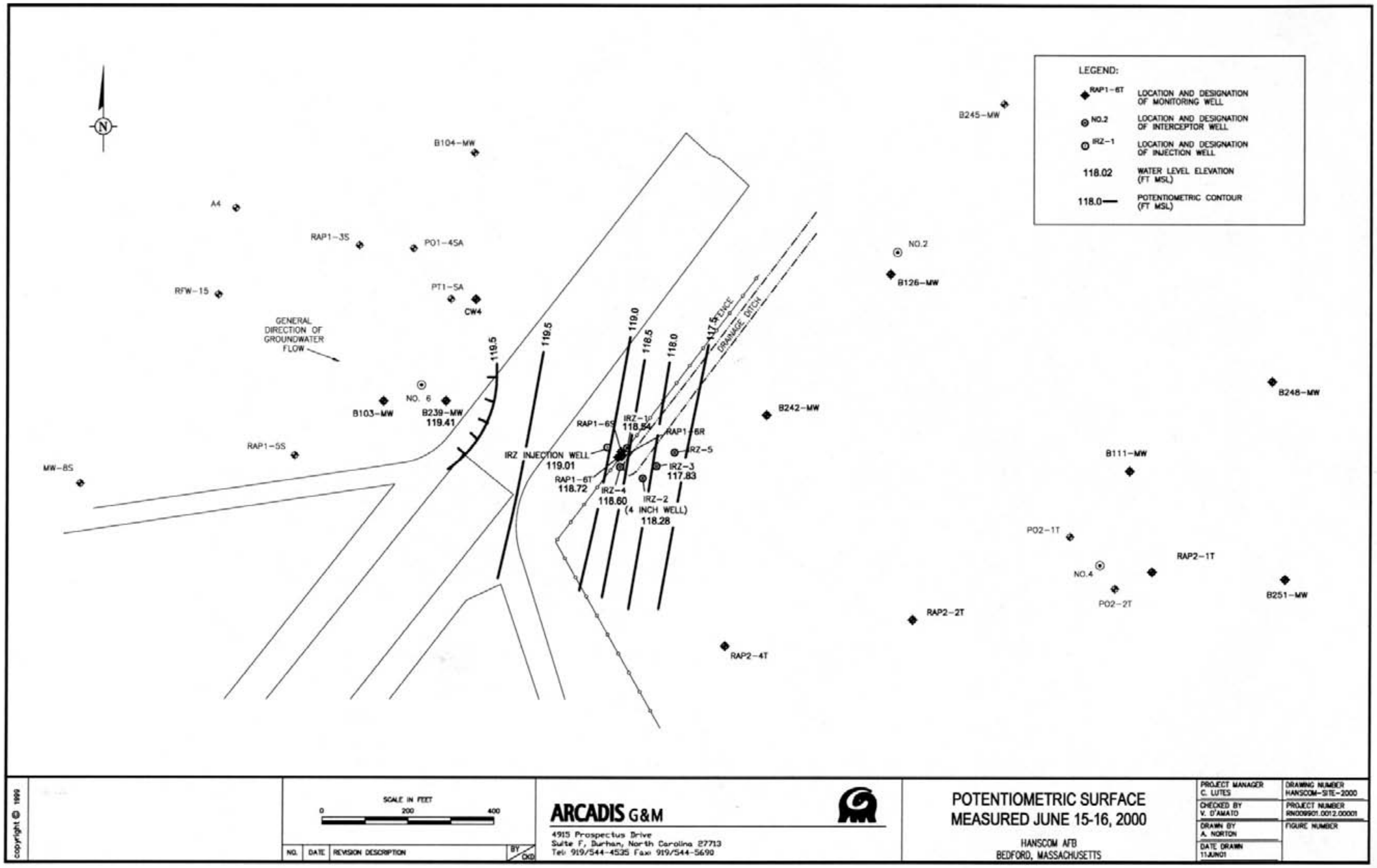


Figure 4-9. Potentiometric Surface Measured 6-15-00 and 6-16-00

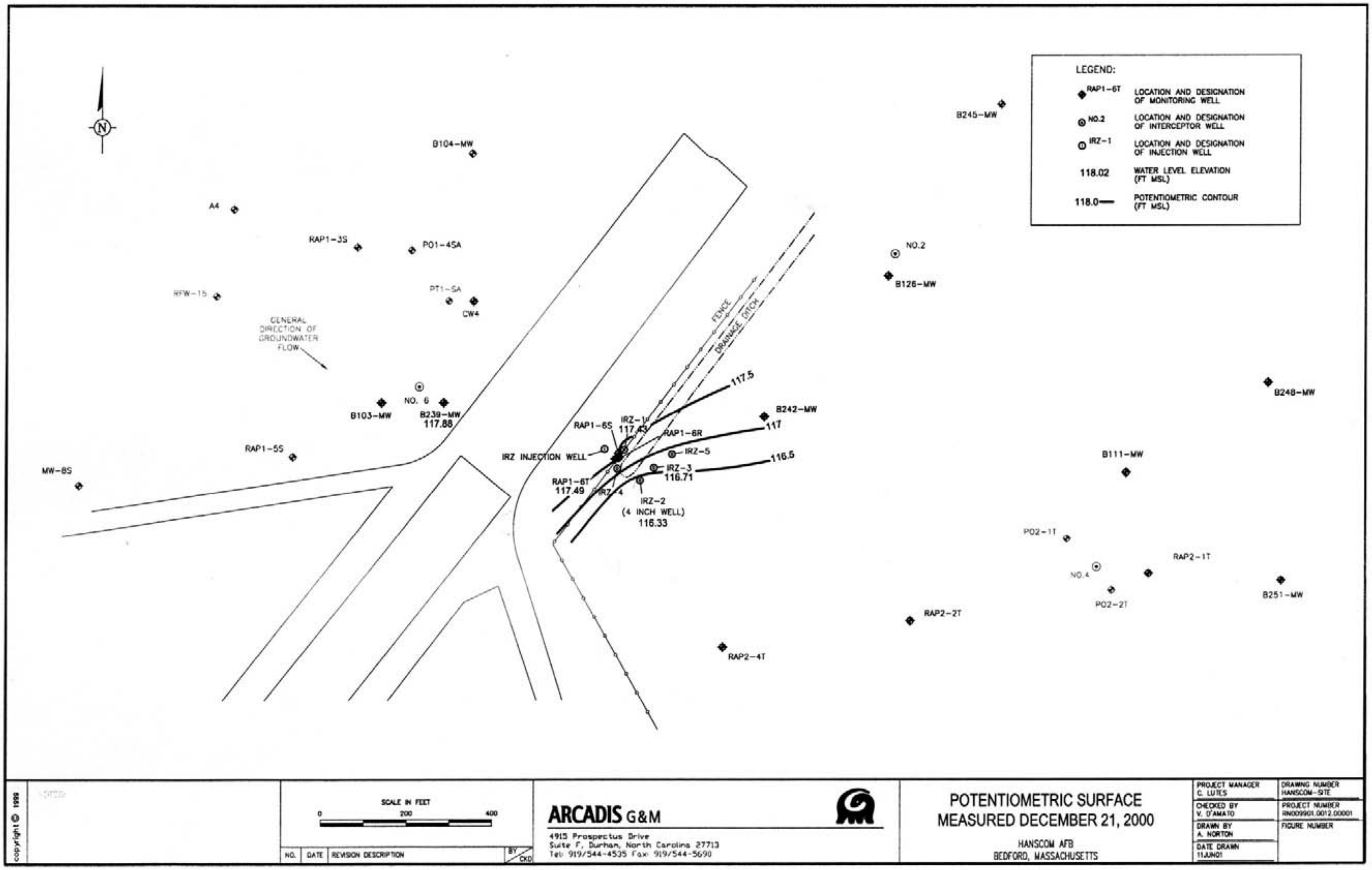


Figure 4-10. Potentiometric Surface Measured 12-21-00

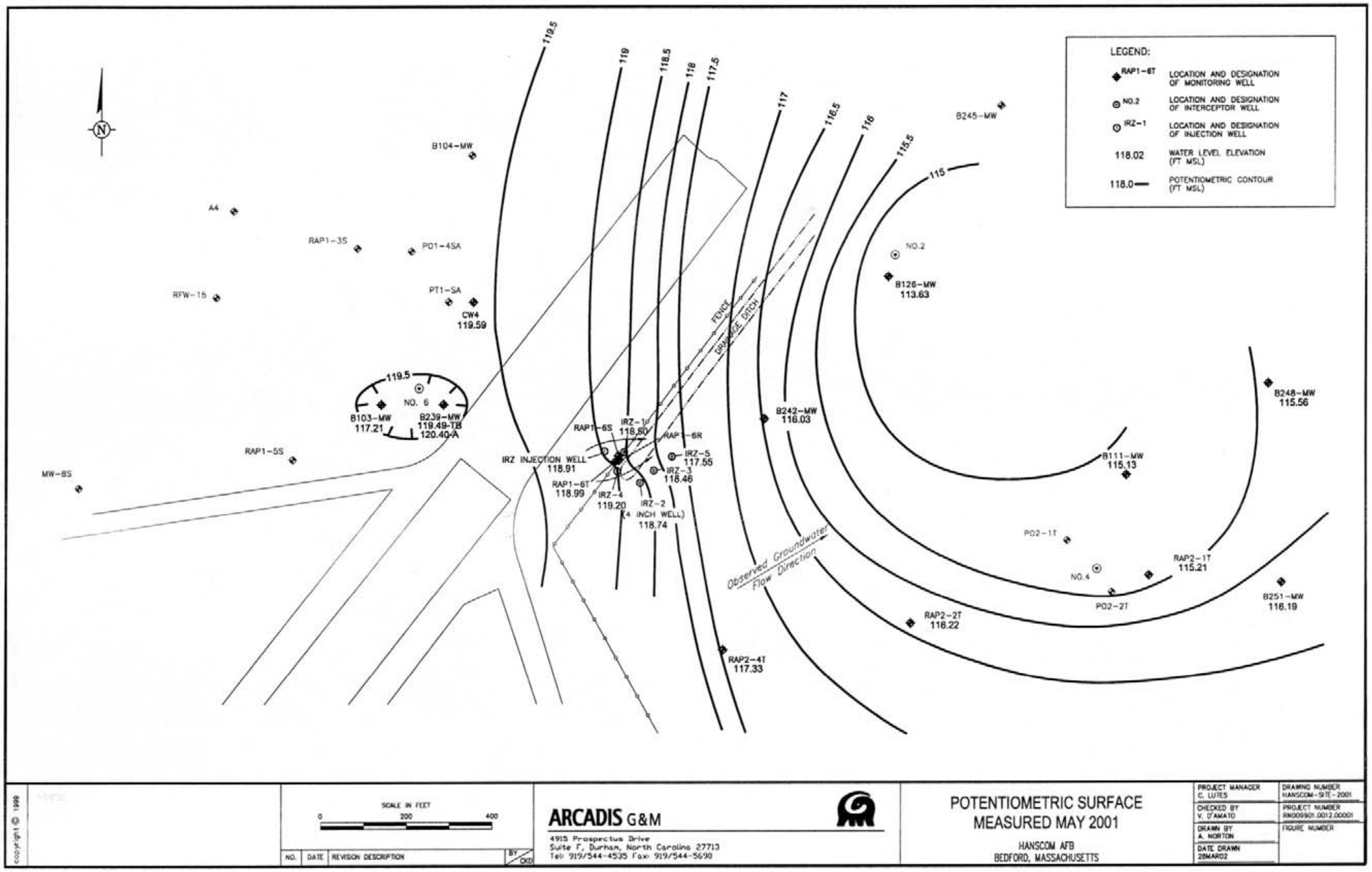


Figure 4-11. Potentiometric Surface as of May 2001

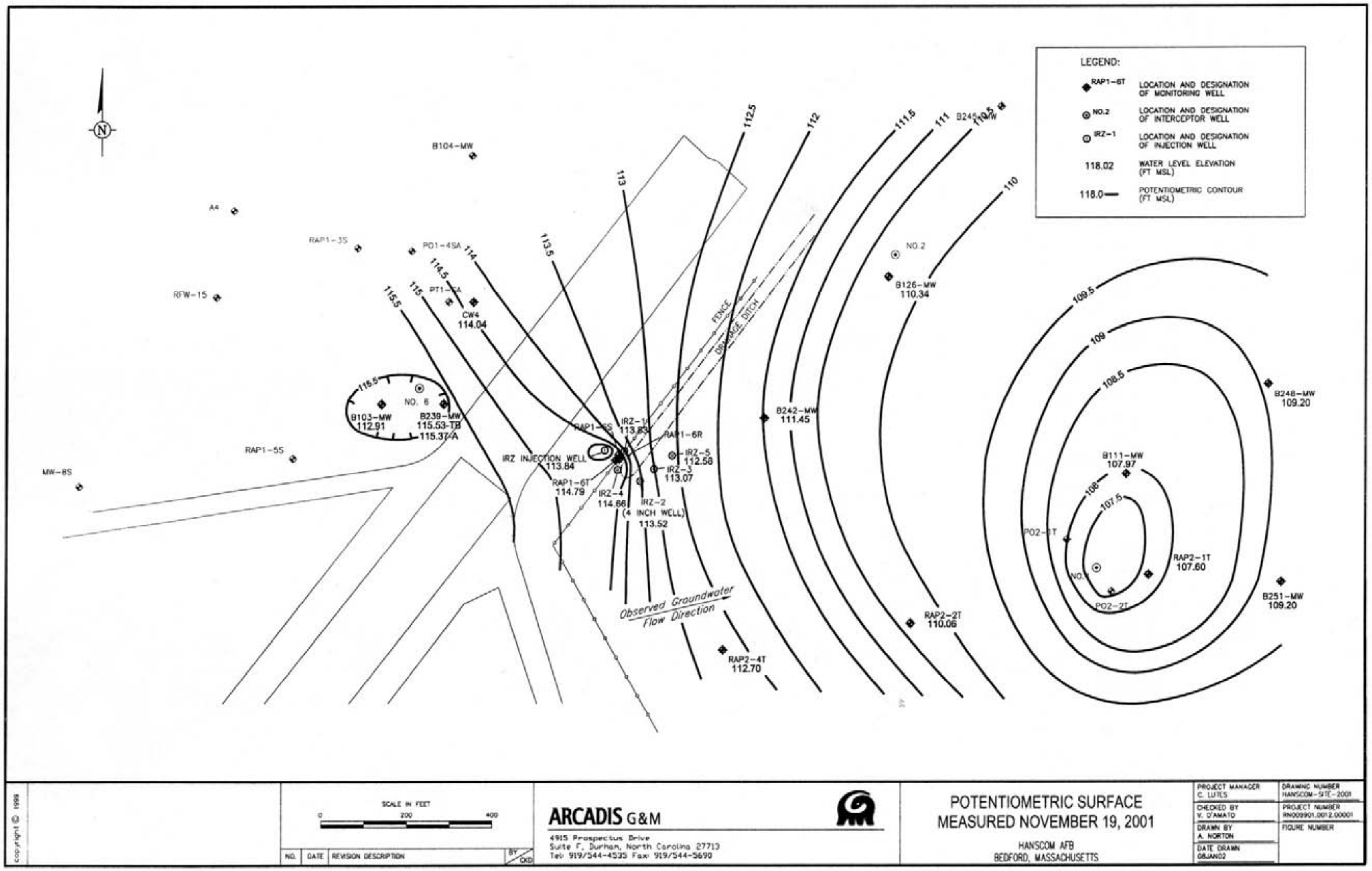


Figure 4-12. Potentiometric Surface as of 11-19-01

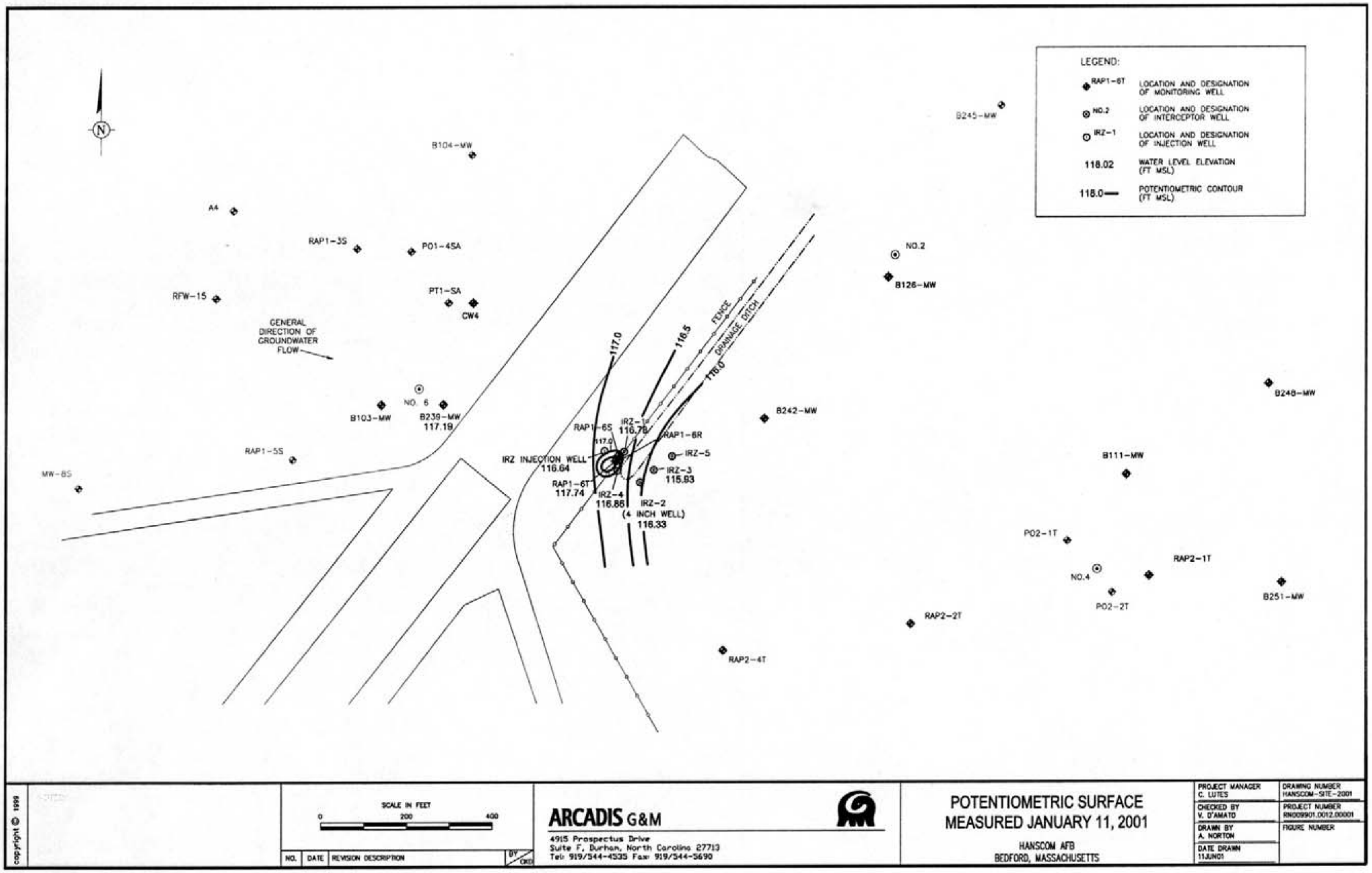


Figure 4-13. Potentiometric Surface as of 1-11-01

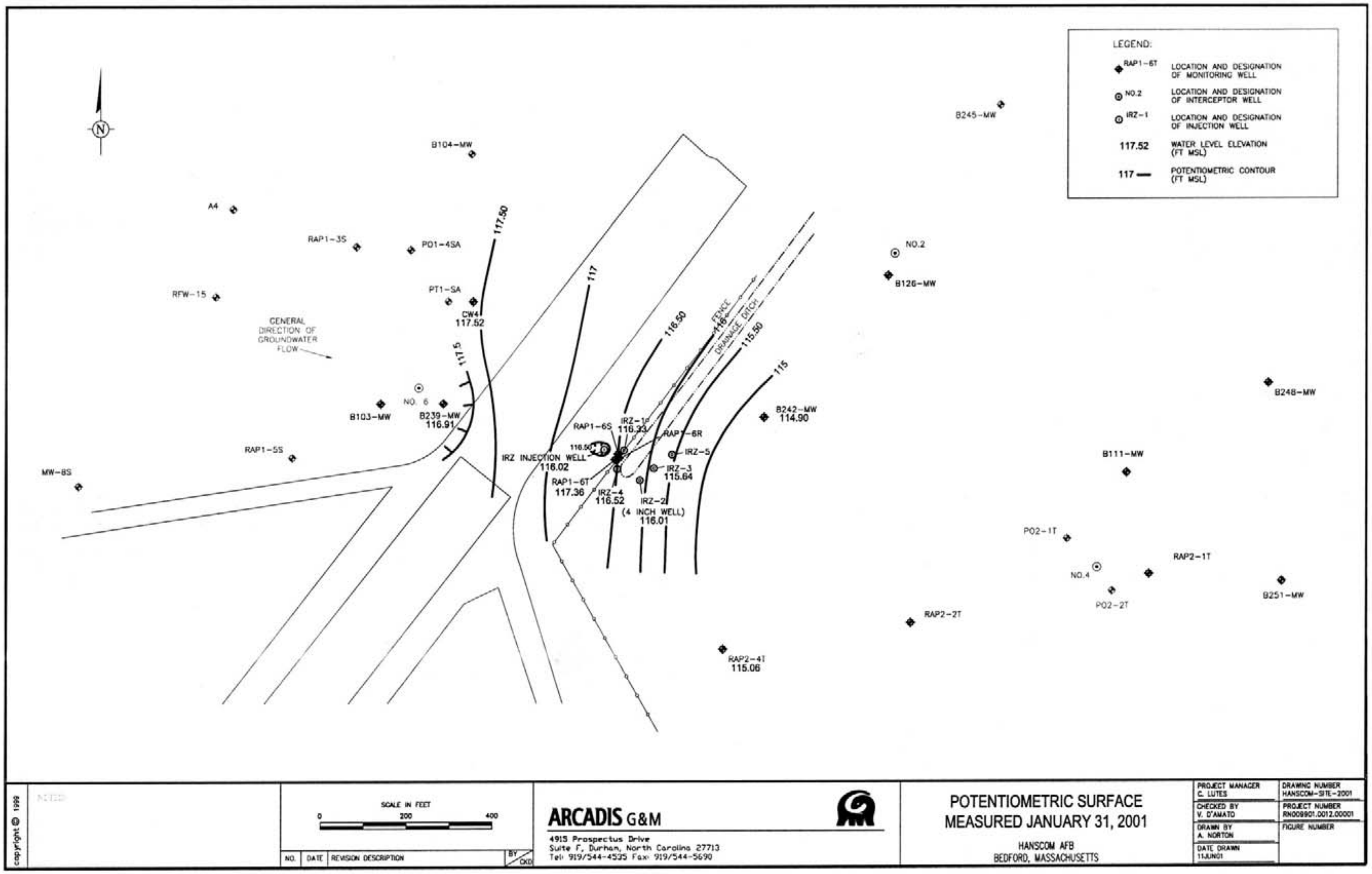


Figure 4-14. Potentiometric Surface as of 1-31-01

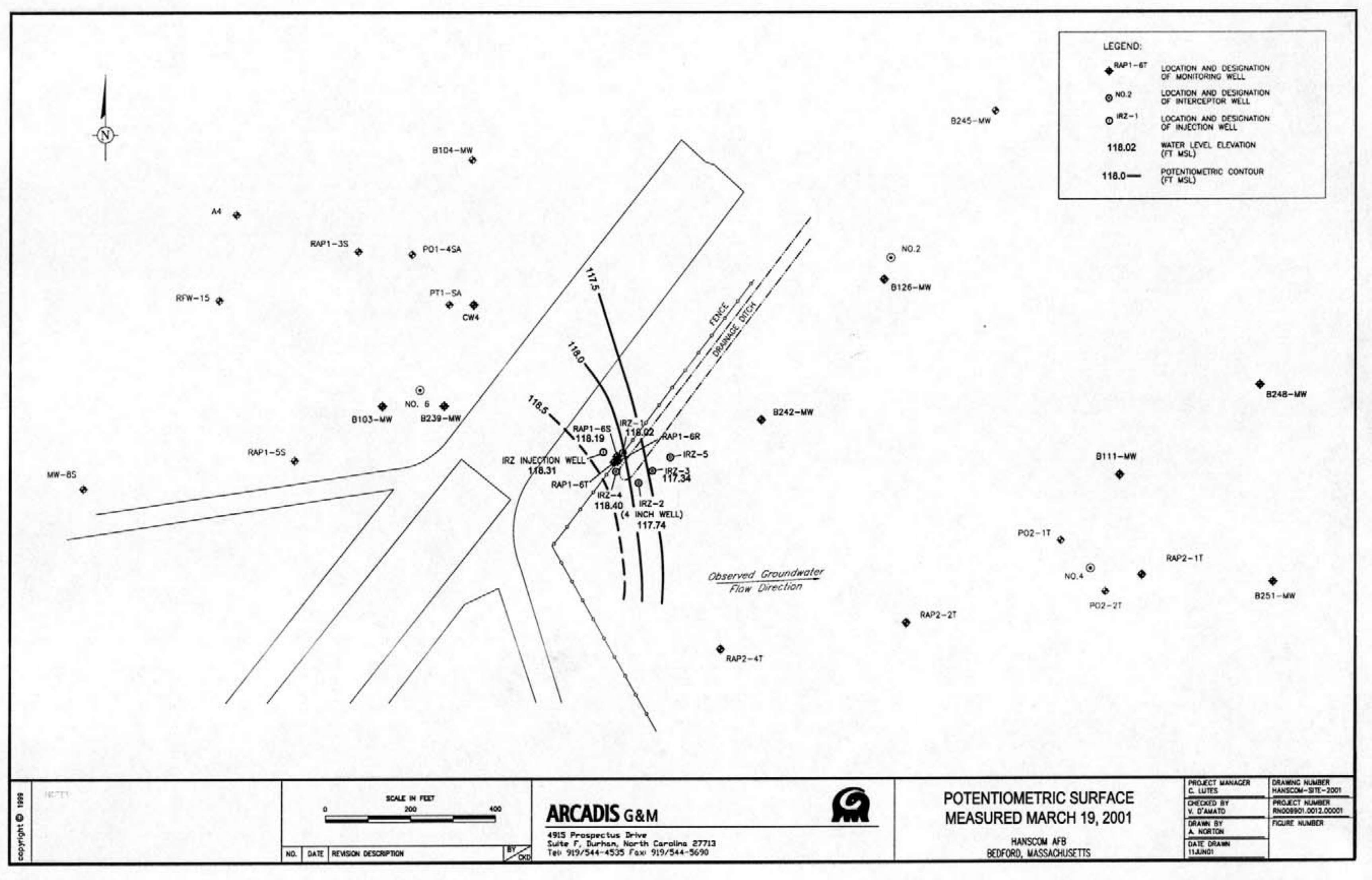


Figure 4-15. Potentiometric Surface as of 3-19-01

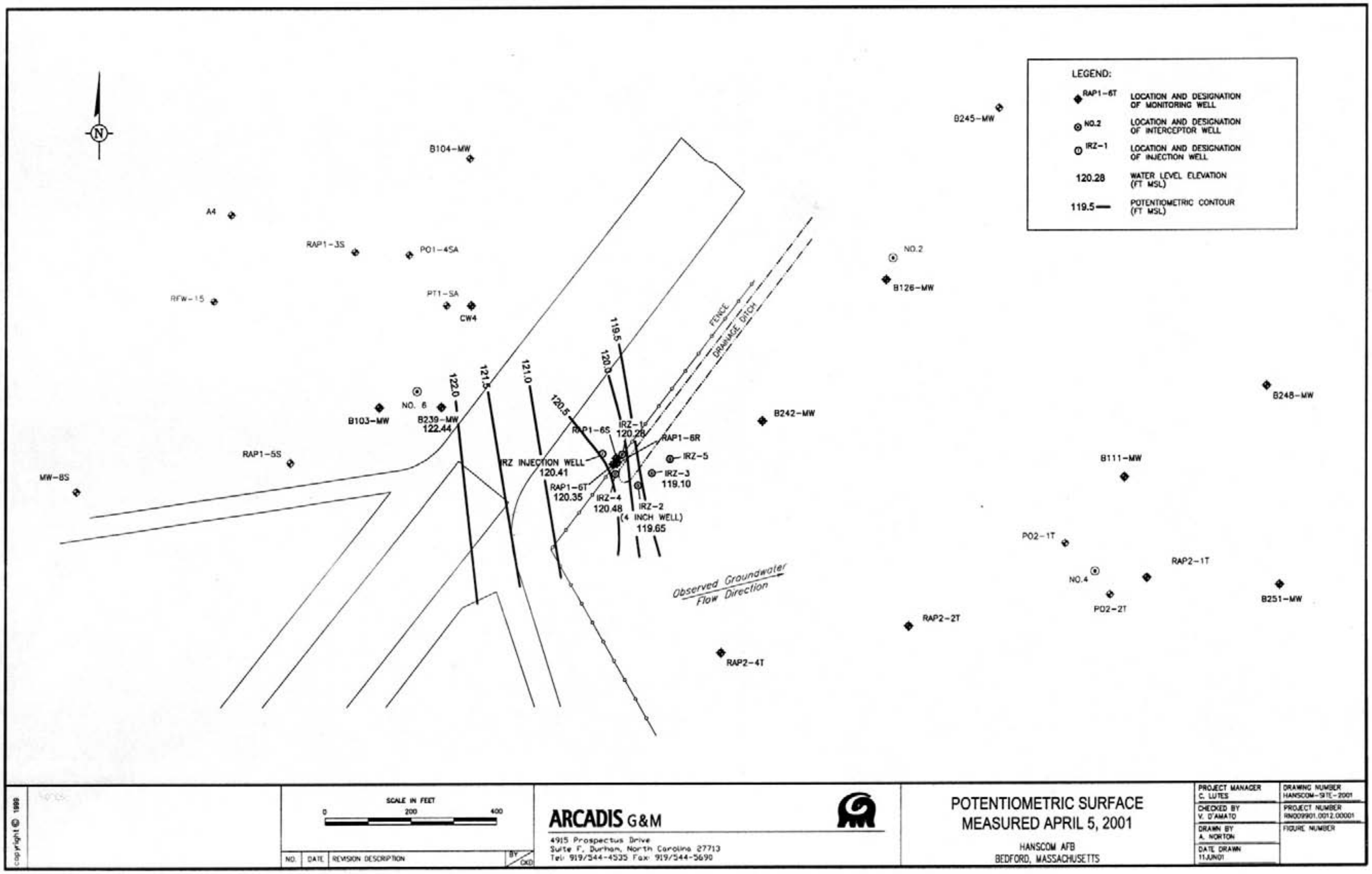


Figure 4-16. Potentiometric Surface as of 4-5-01

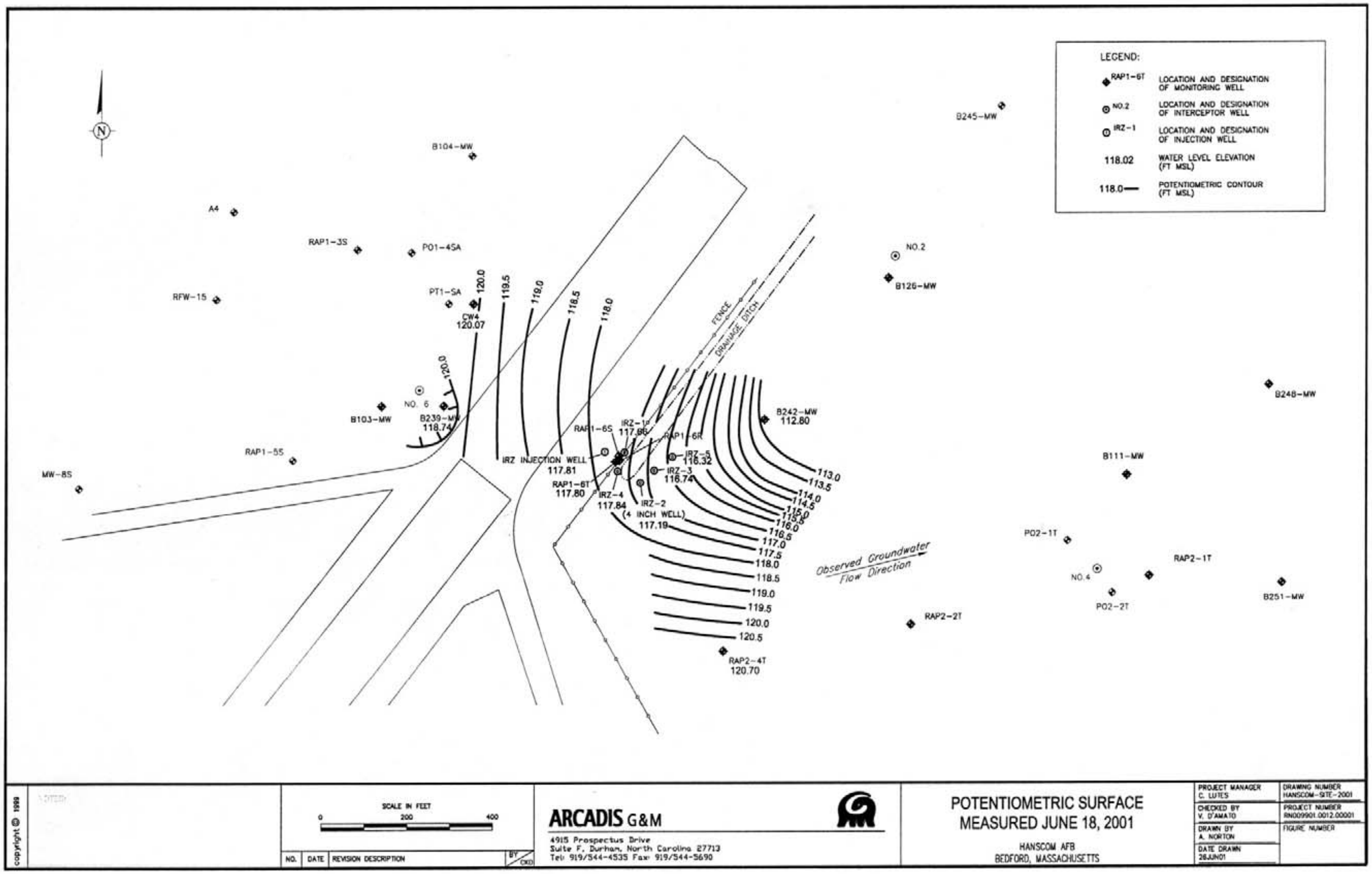


Figure 4-17. Potentiometric Surface as of 6-18-01

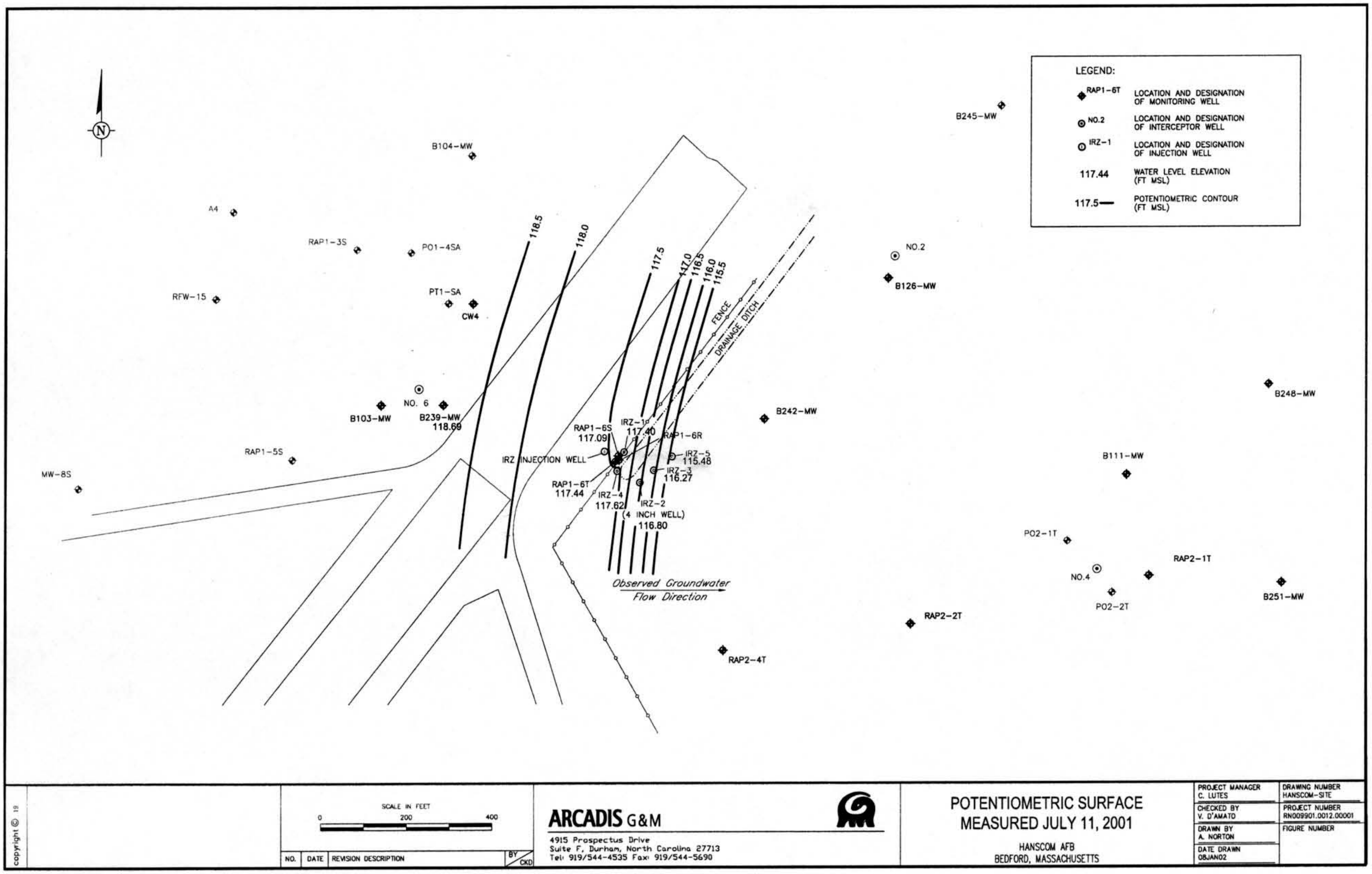


Figure 4-18. Potentiometric Surface as of 7-11-01

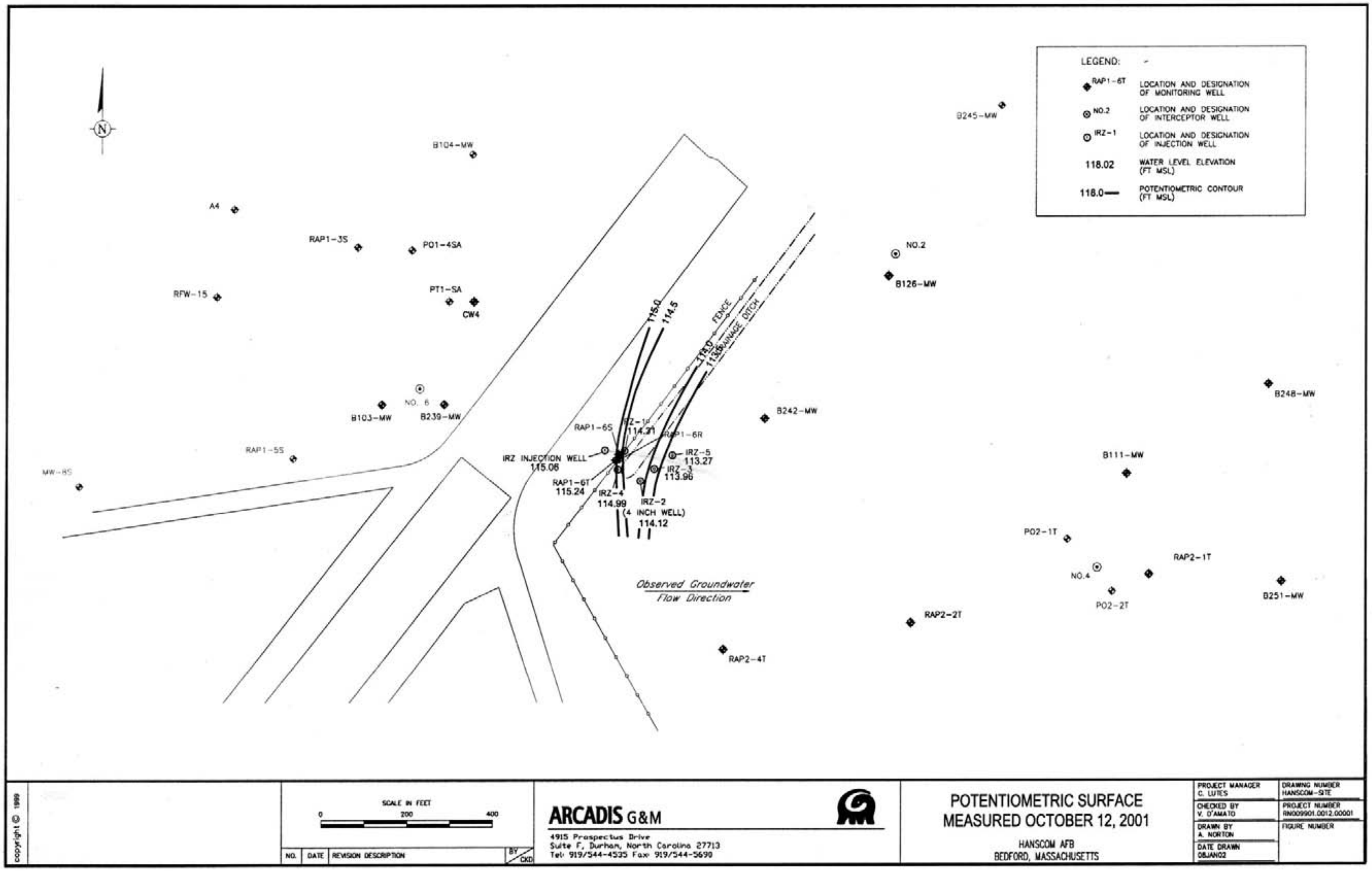


Figure 4-19. Potentiometric Surface as of 10-12-01

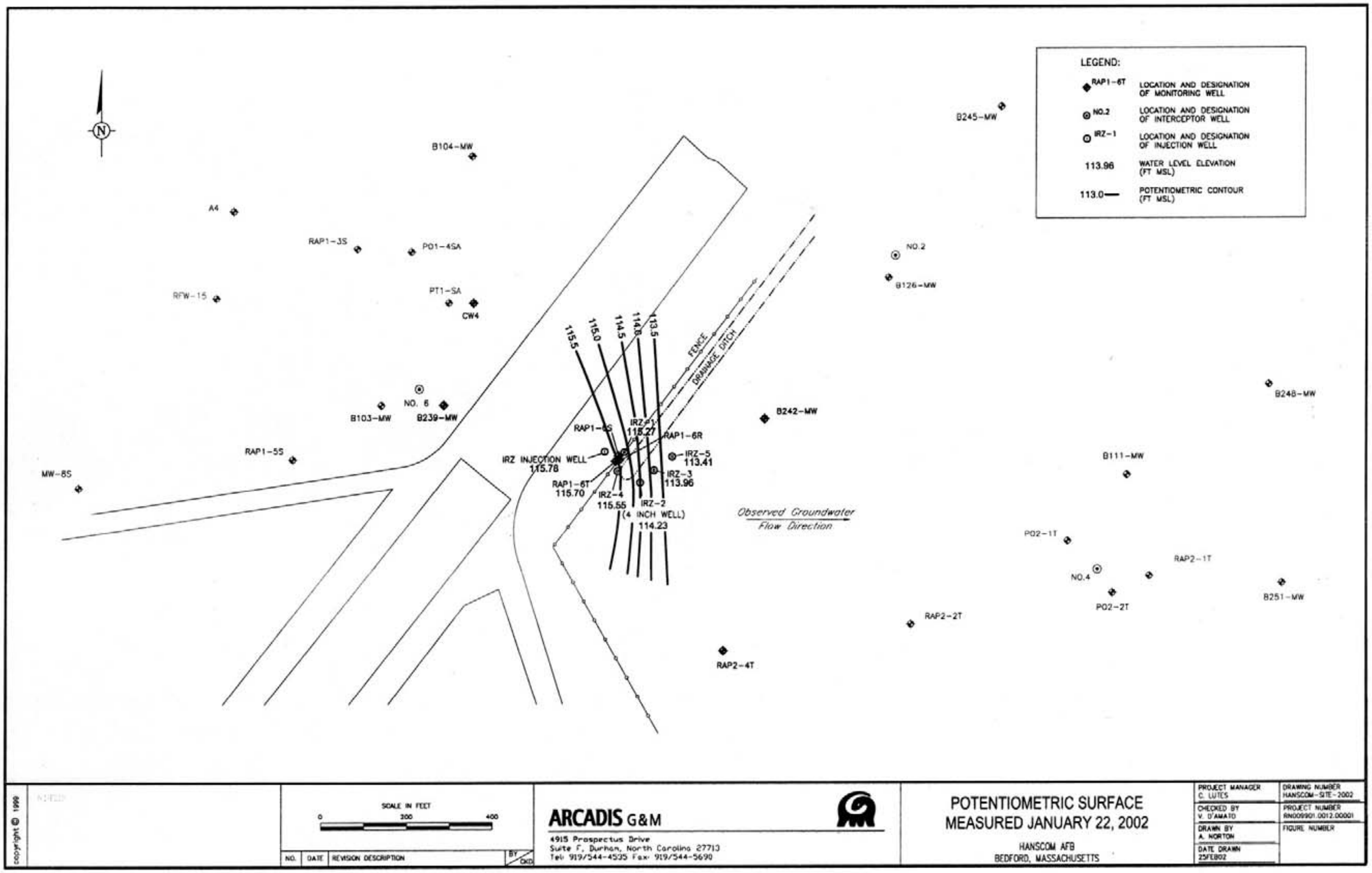


Figure 4-20. Potentiometric Surface as of 1-22-02

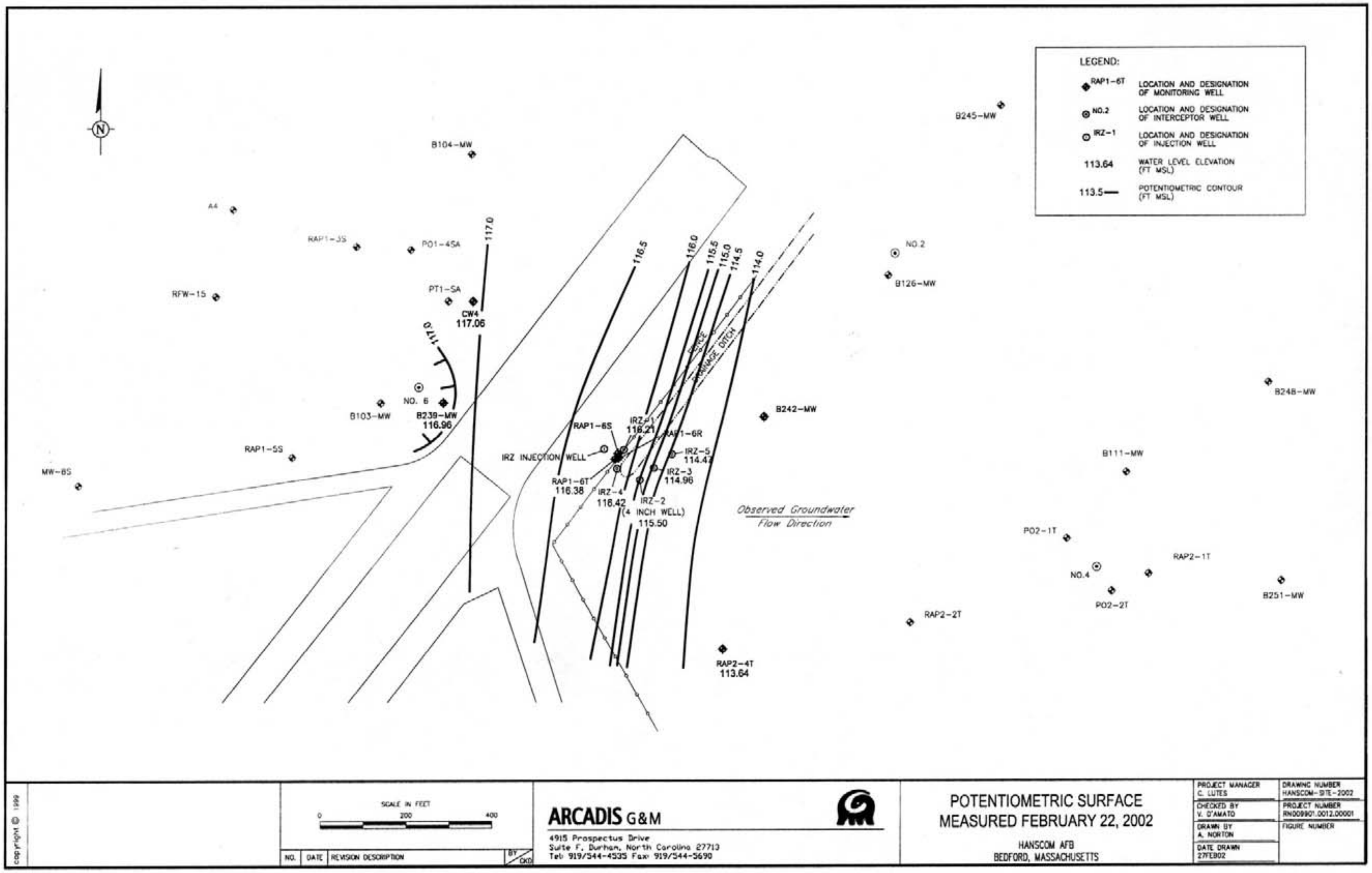


Figure 4-21. Potentiometric Surface as of 2-22-02

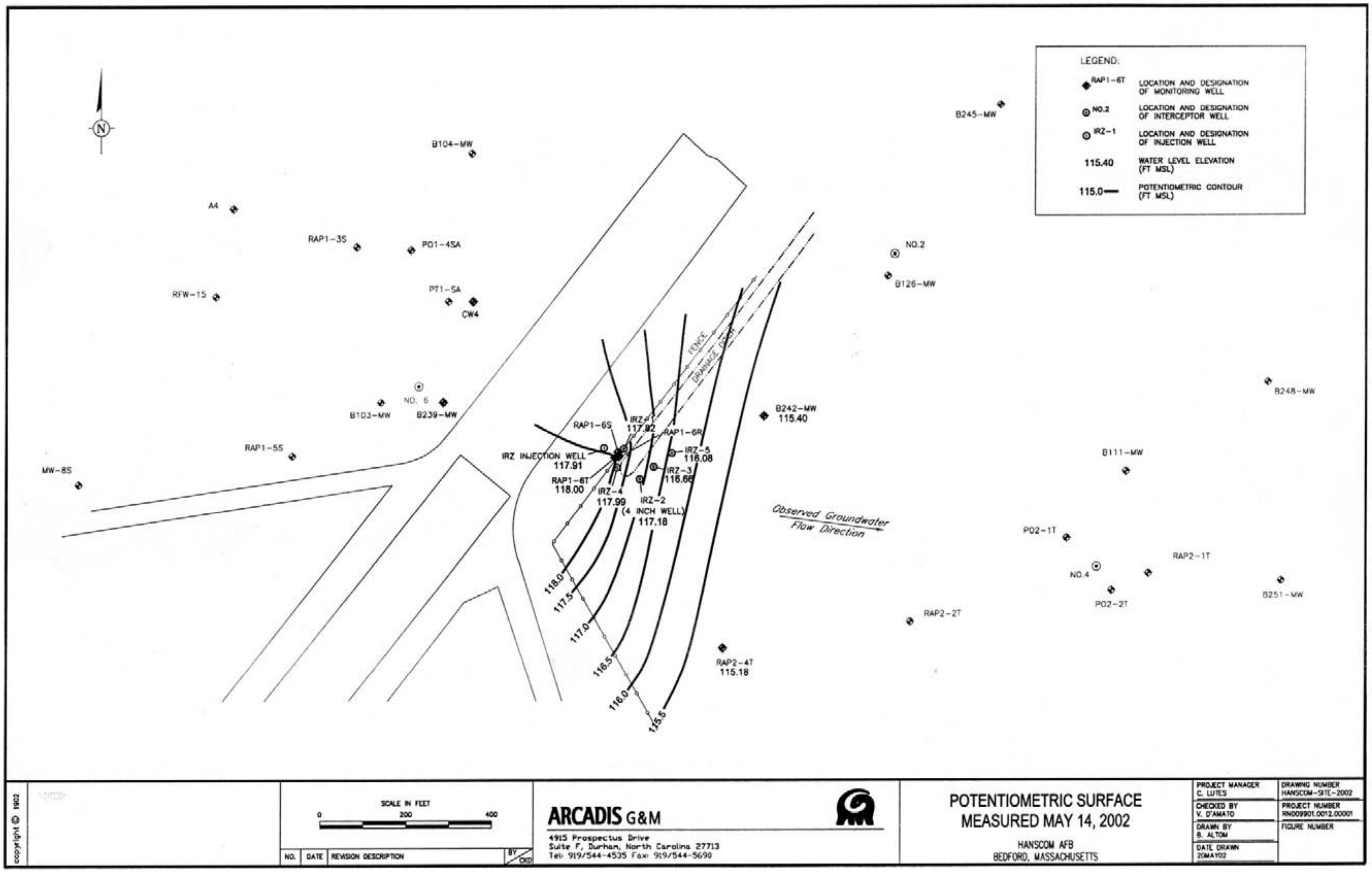


Figure 4-22. Potentiometric Surface as of 5-14-02

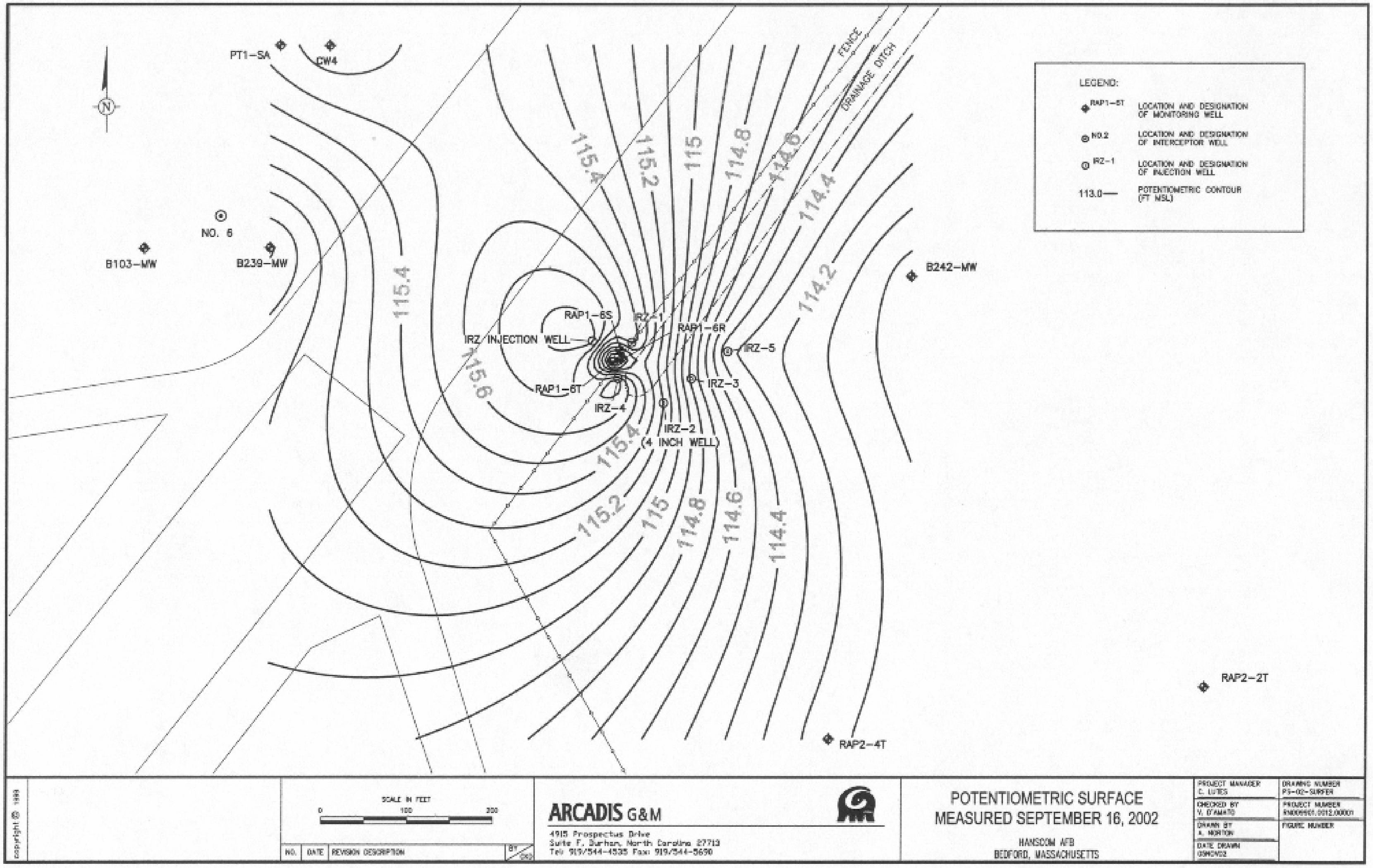


Figure 4-23. Potentiometric Surface as of 9-16-02

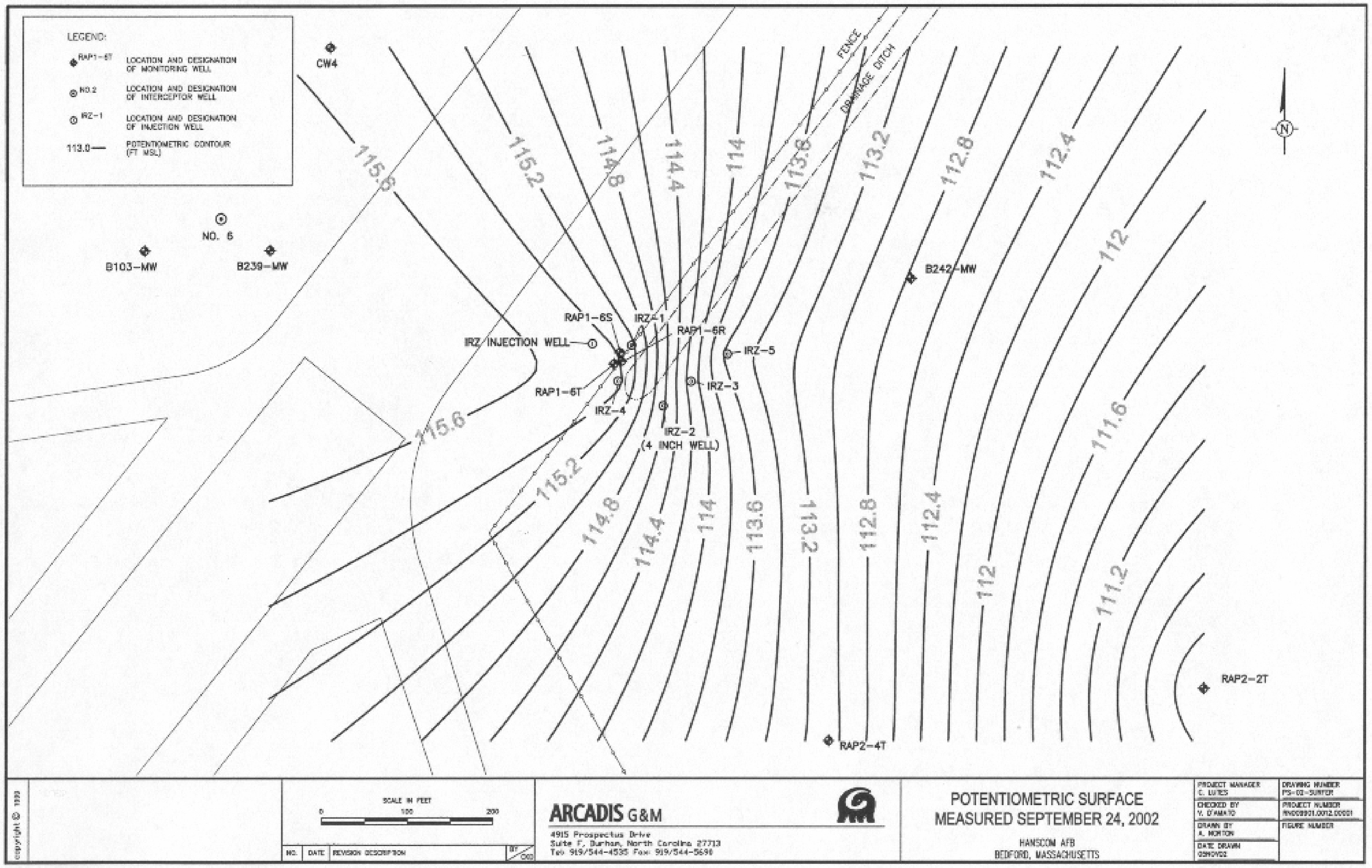


Figure 4-24. Potentiometric Surface as of 9-24-02

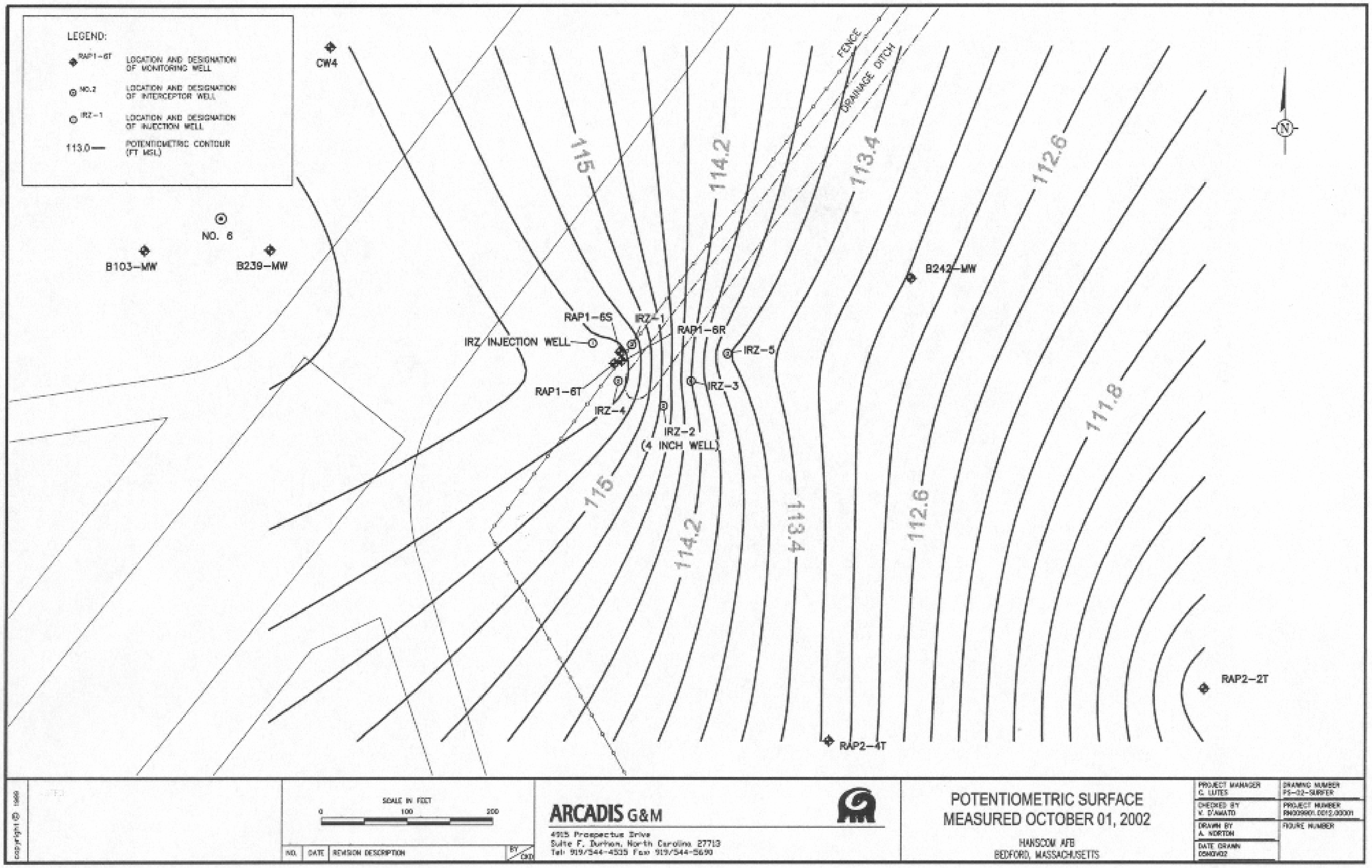


Figure 4-25. Potentiometric Surface as of 10-1-02

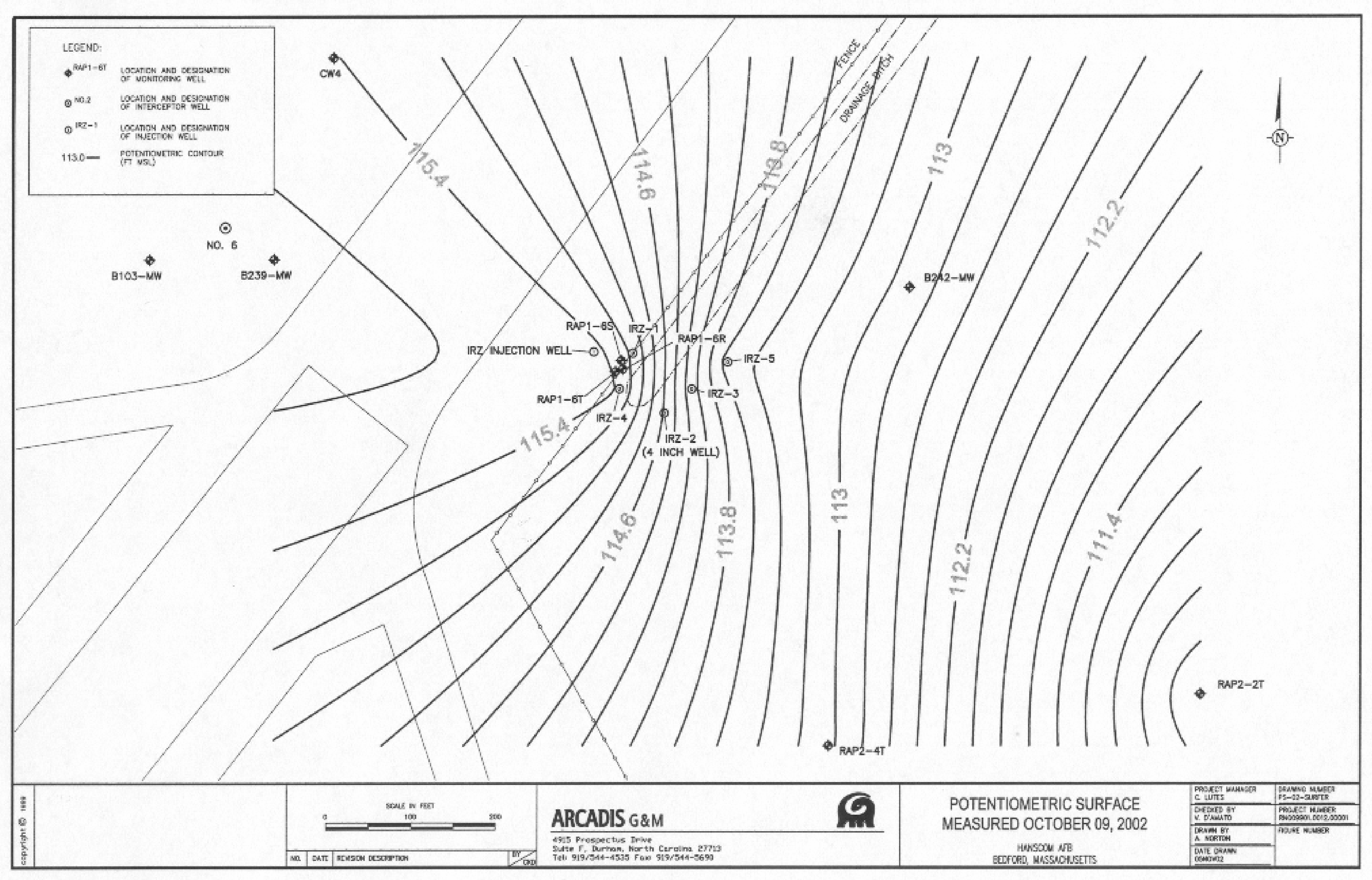


Figure 4-26. Potentiometric Surface as of 10-9-02

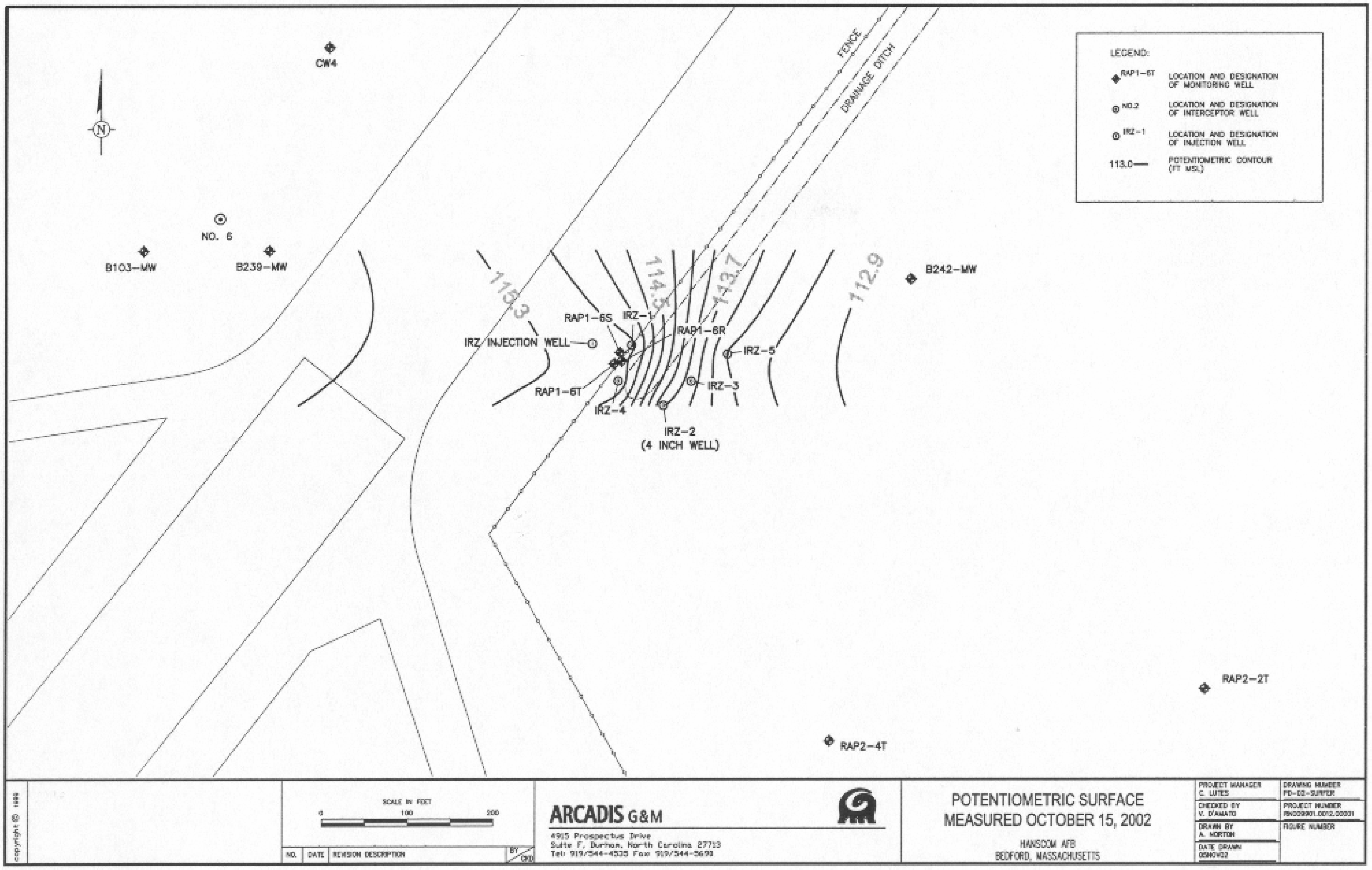


Figure 4-27. Potentiometric Surface as of 10-15-02

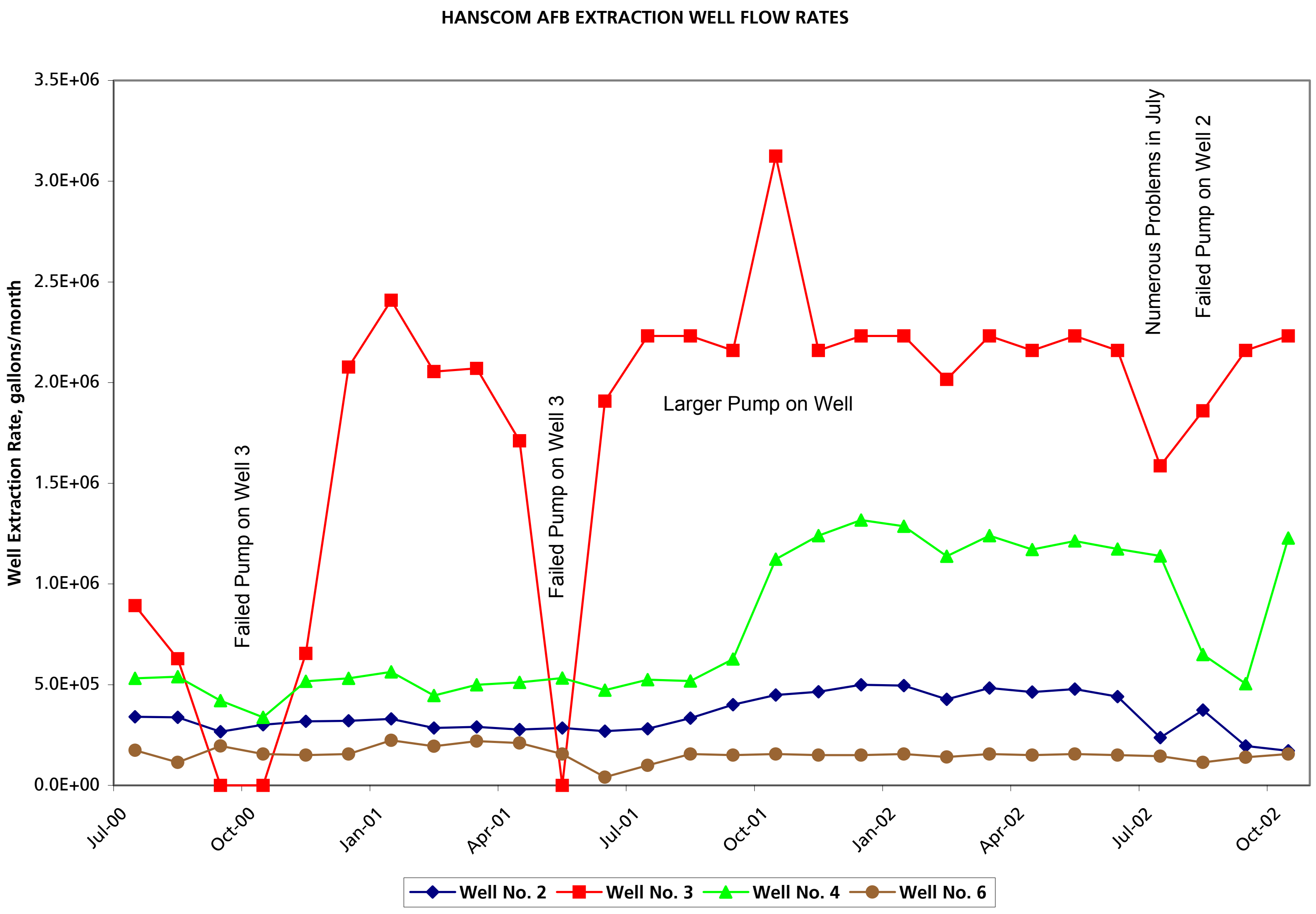


Figure 4-28. Extraction Well Flow Rates

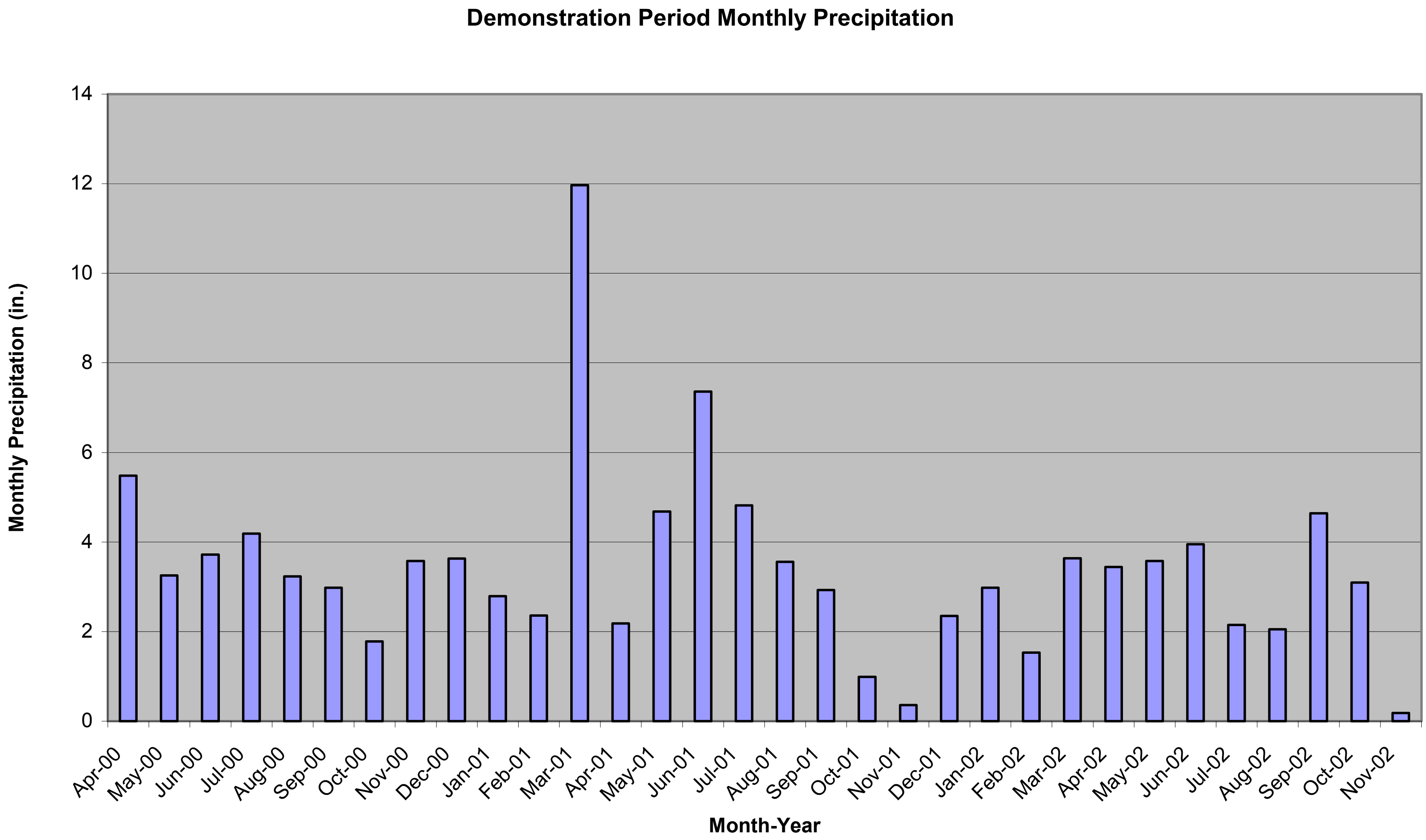


Figure 4-29. Monthly Precipitation

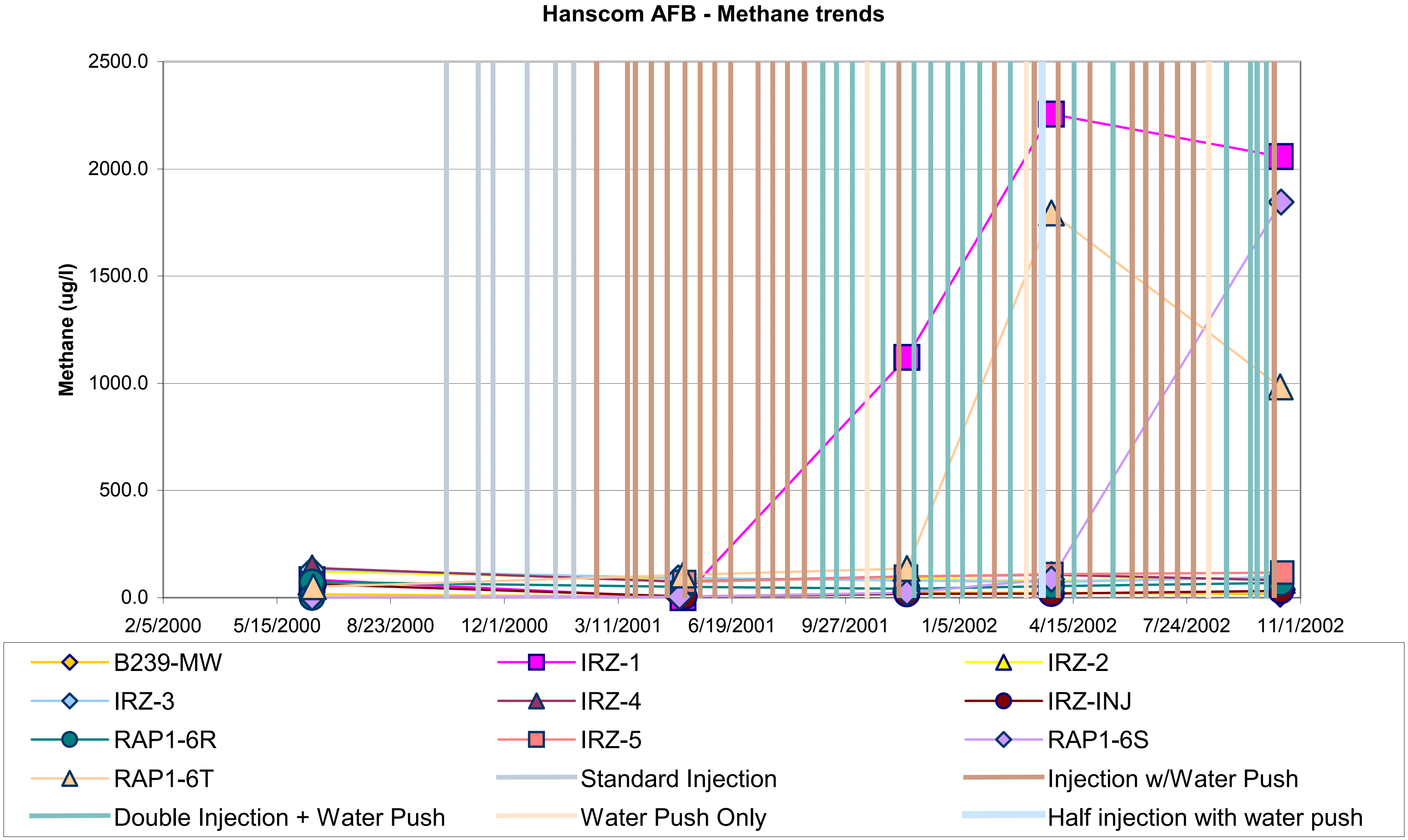


Figure 4-30. Methane Trends

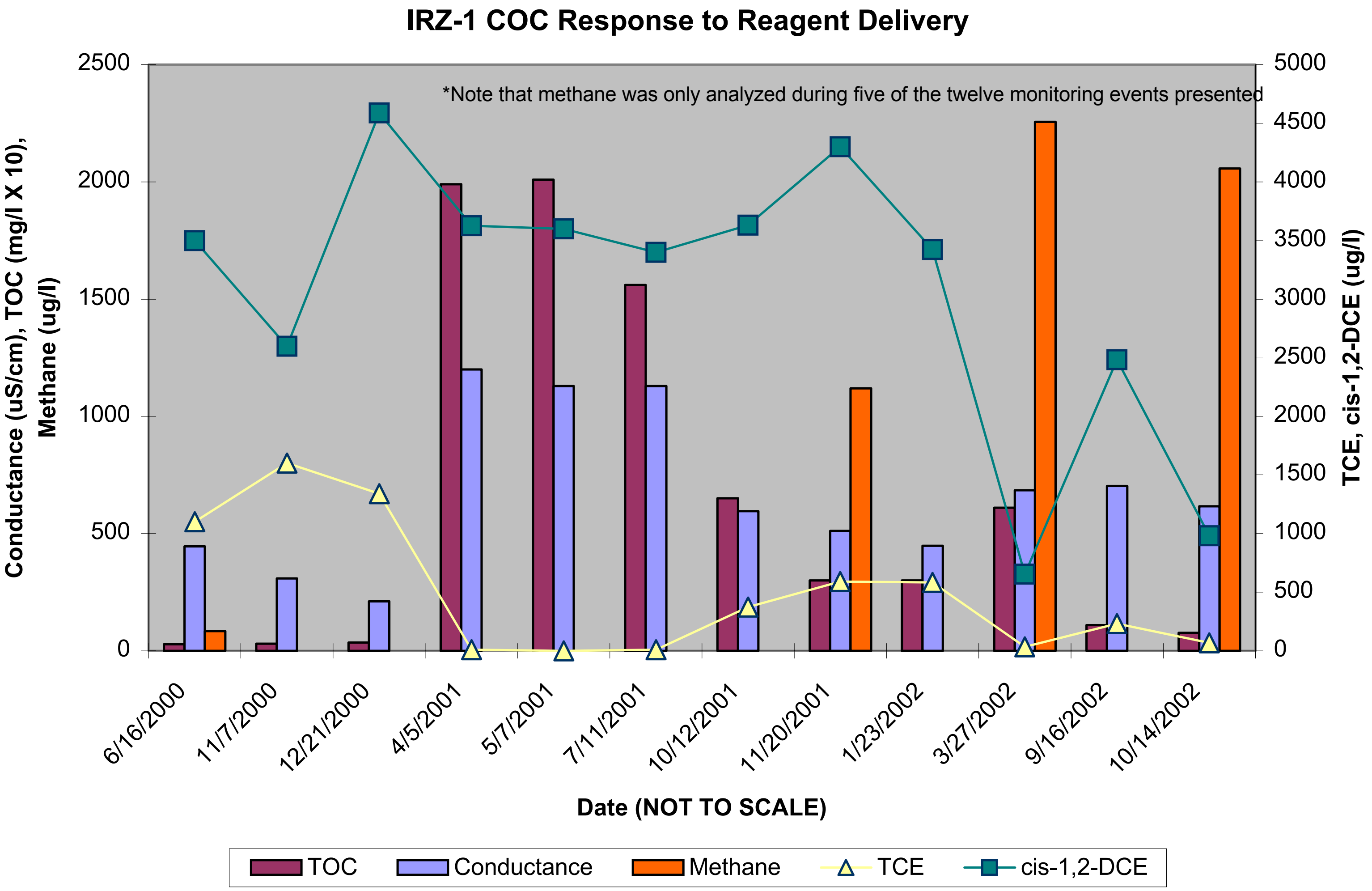


Figure 4-31. IRZ-1 COC Response to Reagent Delivery

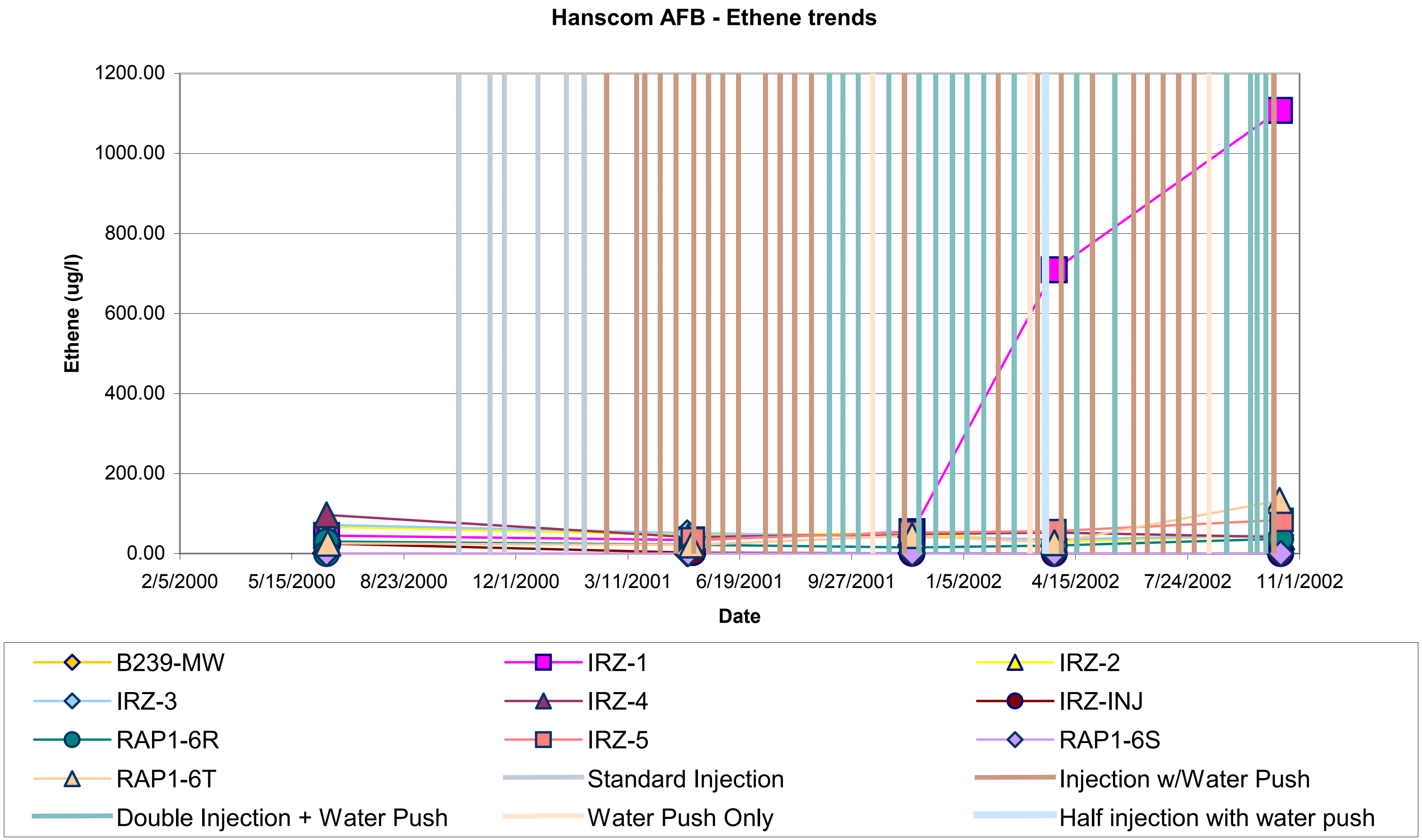


Figure 4-32. Ethene Trends

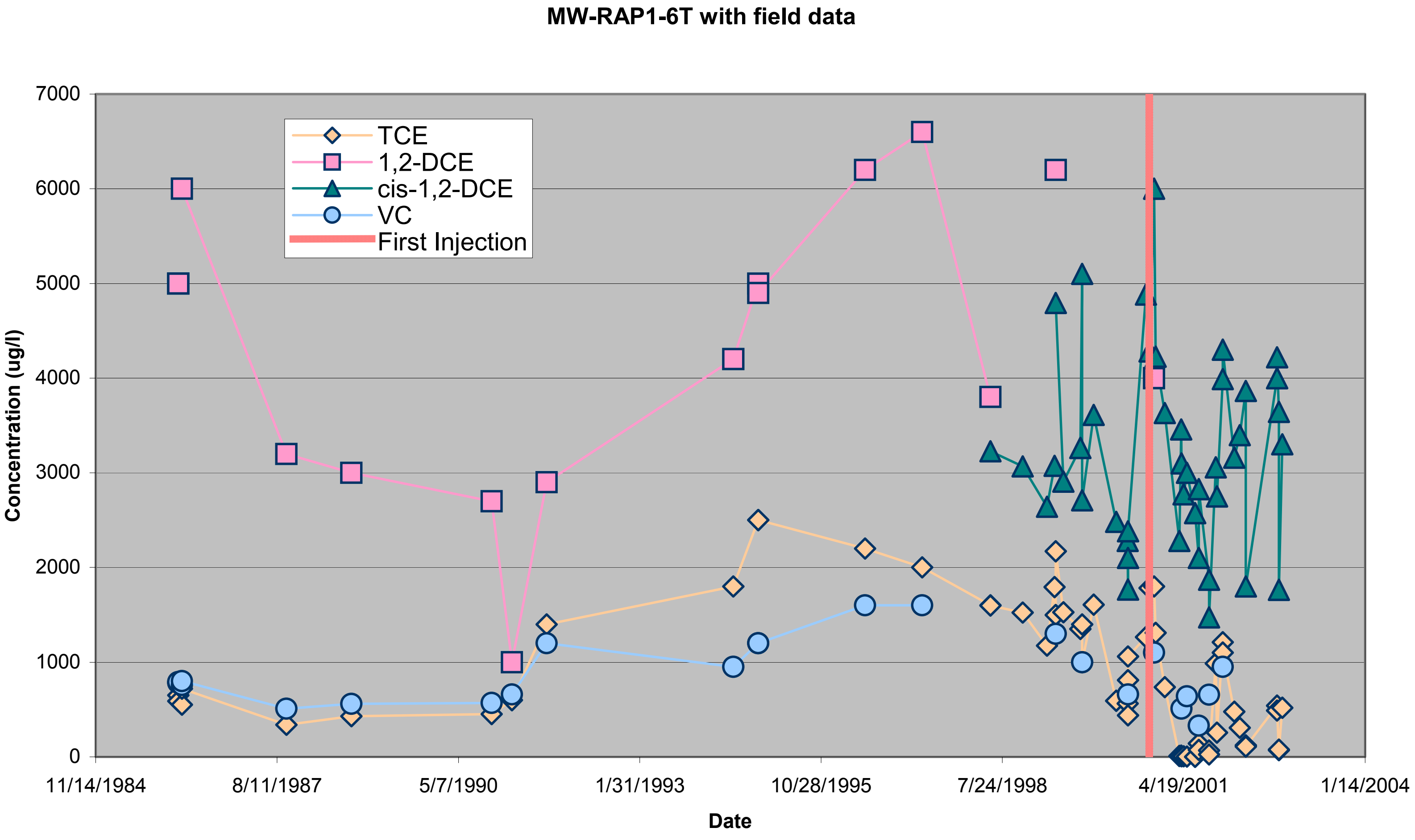


Figure 4-33. Historical VOC Trends for RAP1-6T Showing Both Laboratory and Field-Generated Data

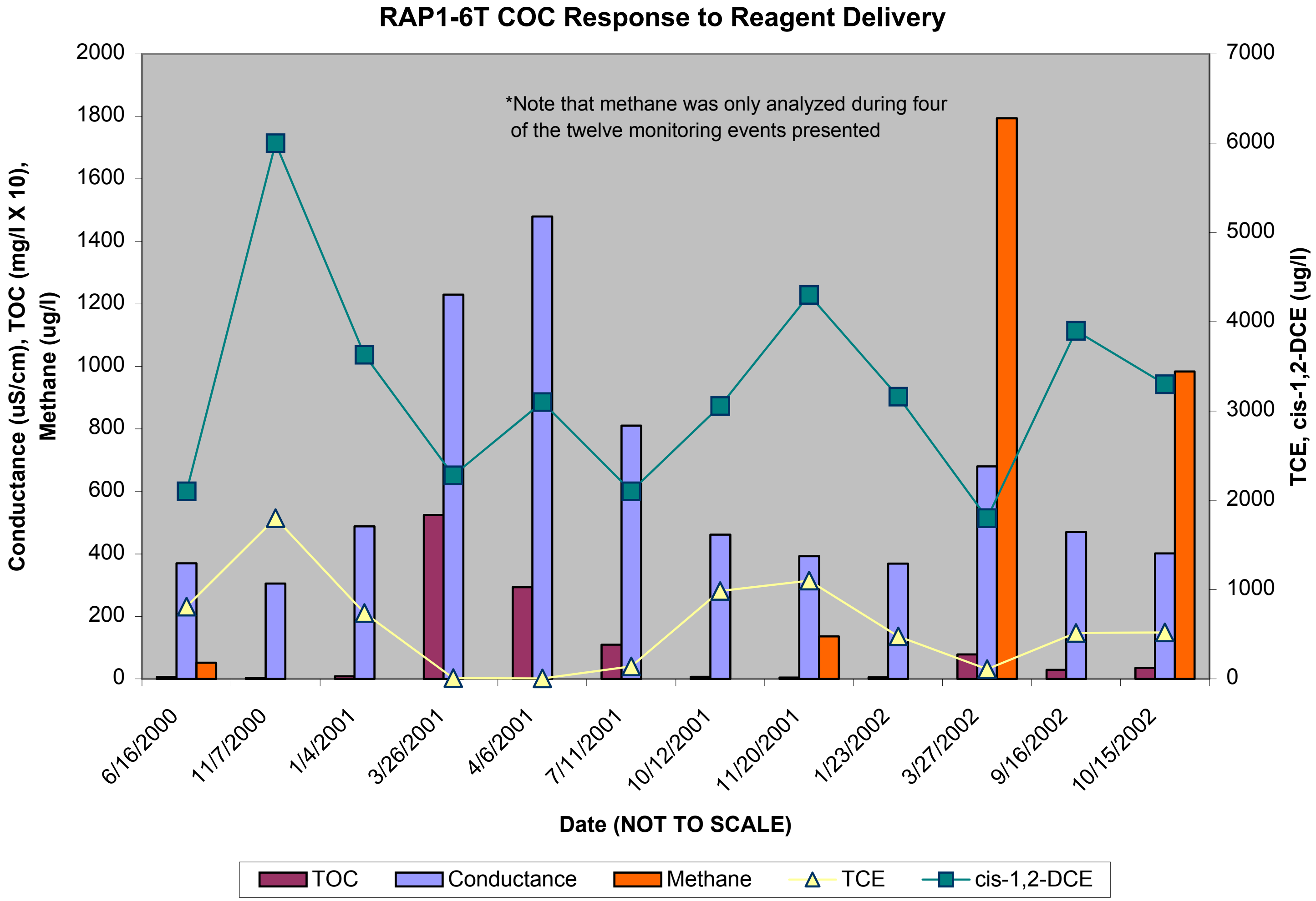


Figure 4-34. RAP1-6T COC Response to Reagent Delivery

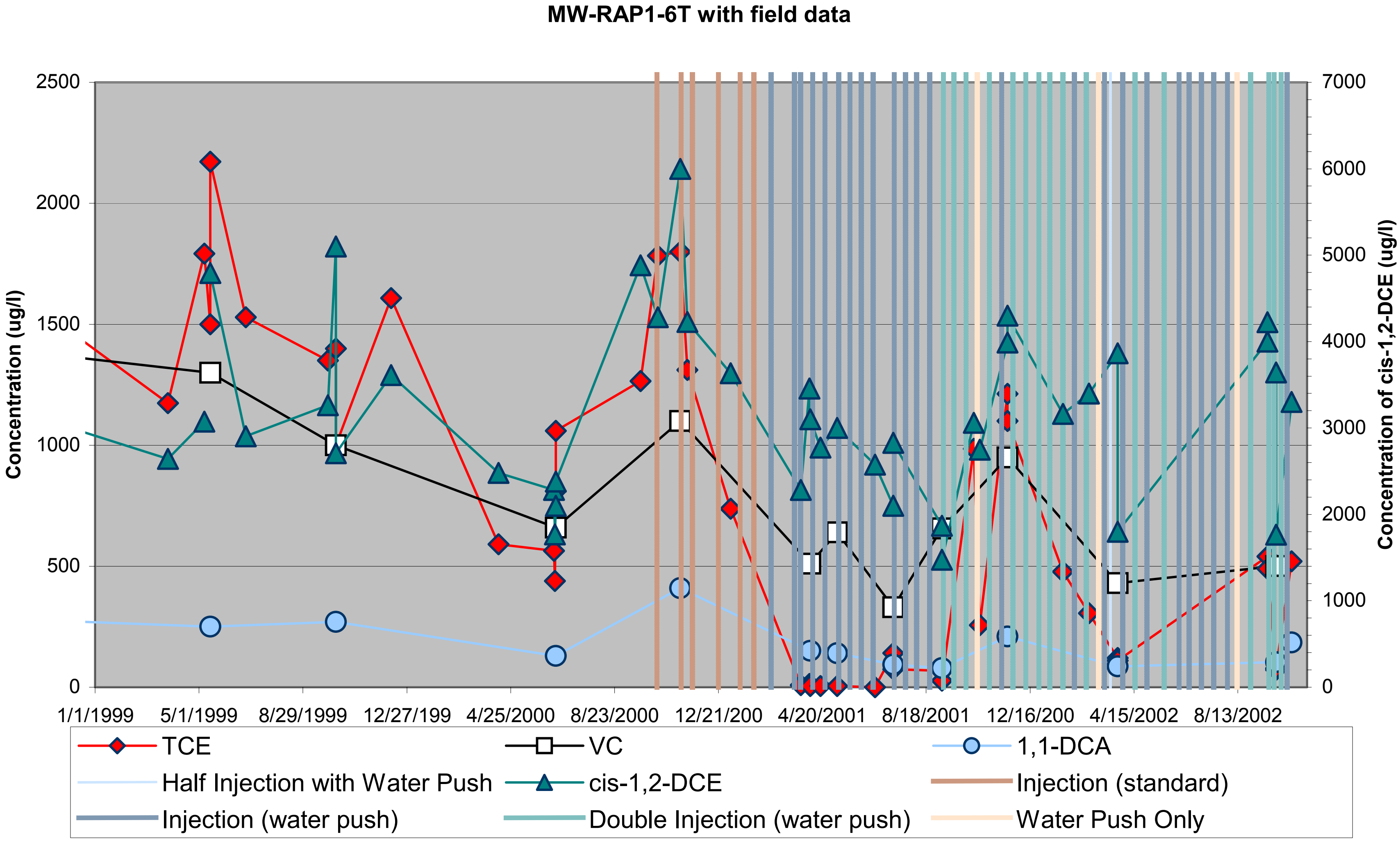


Figure 4-35. Recent VOC Trends for RAP1-6T Showing Both Laboratory and Field-Generated Data

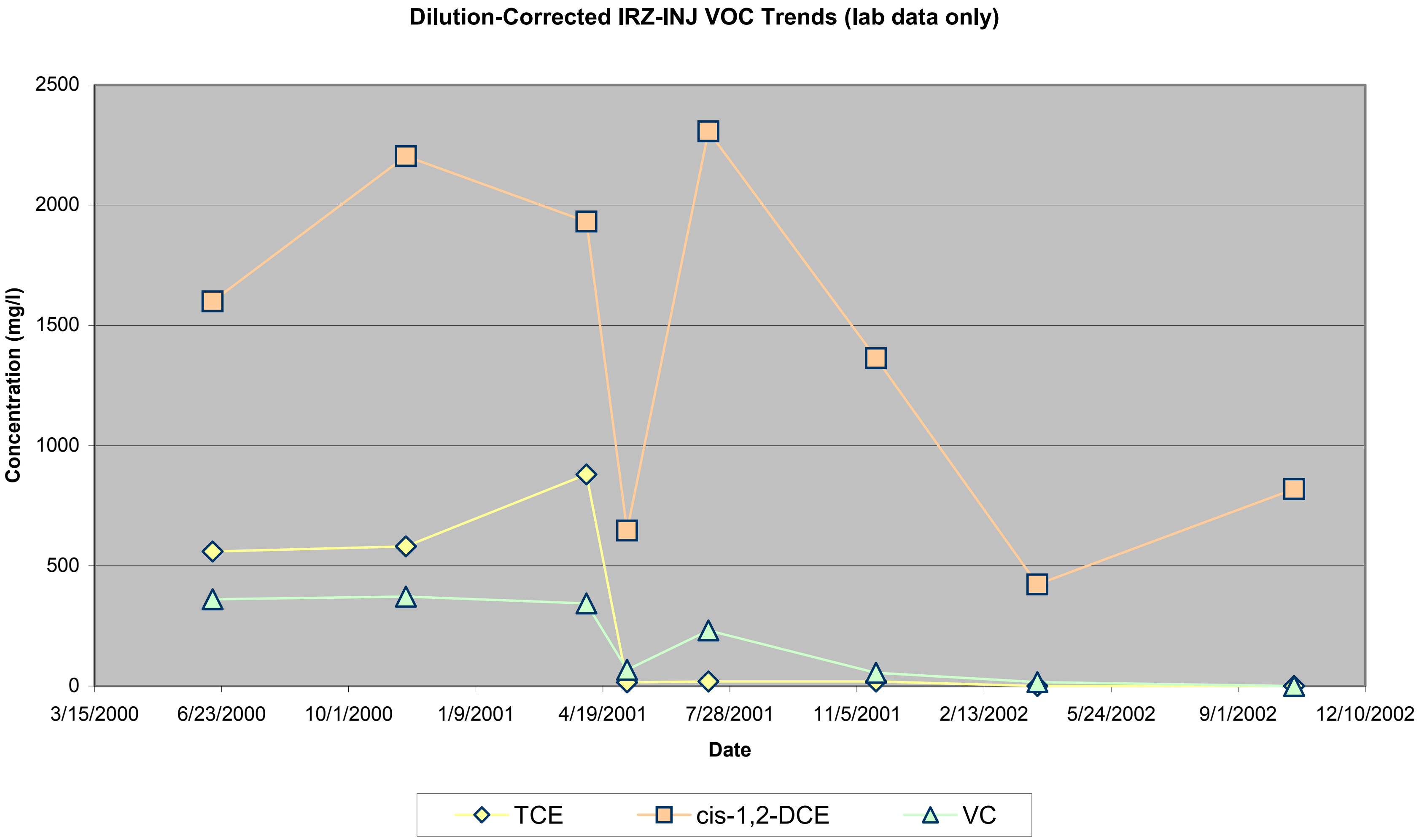
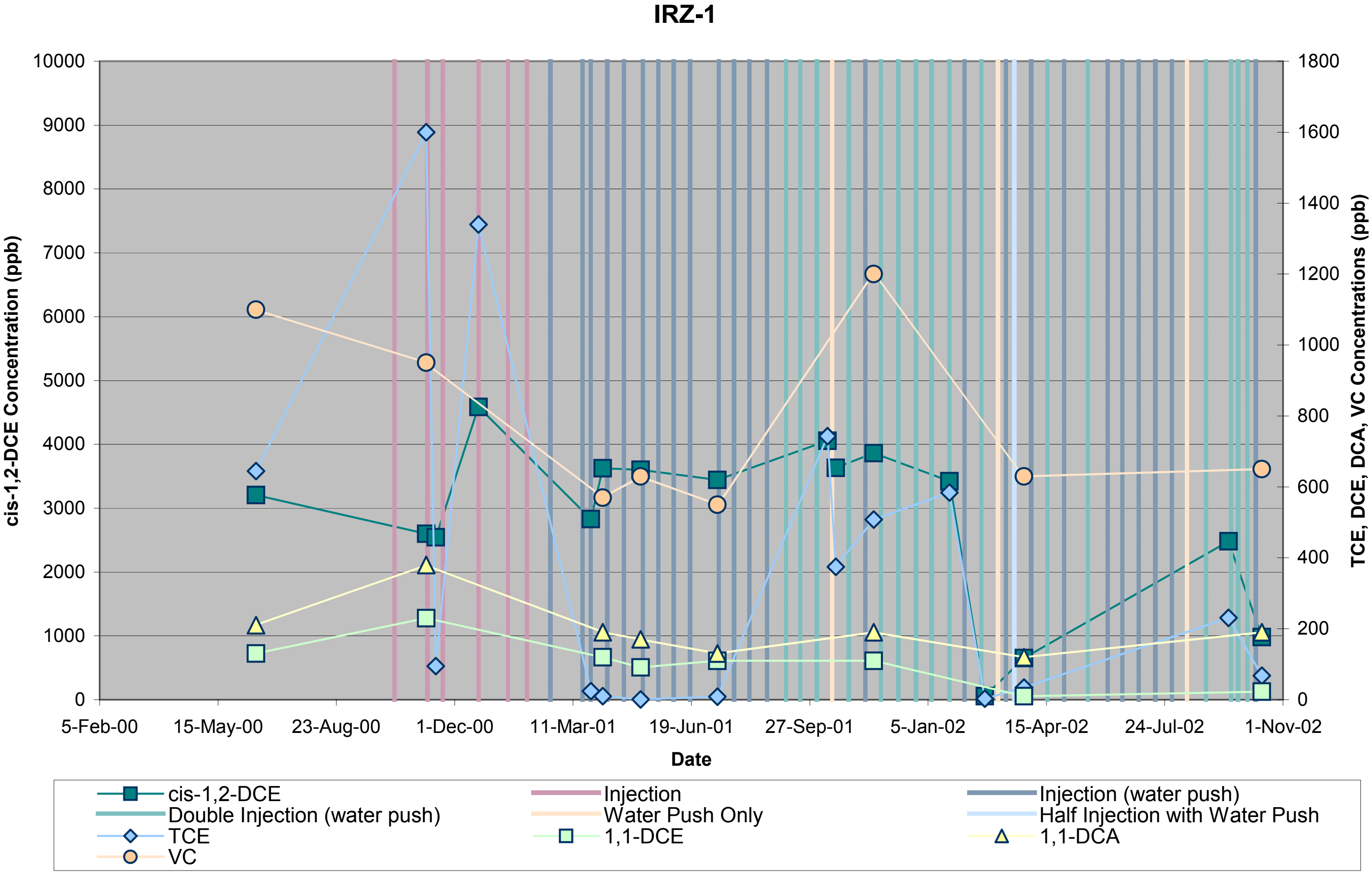


Figure 4-36. Dilution-Corrected IRZ-INJ VOC Trends (Lab Data Only)



Note: On dates when both field and laboratory measurements were taken, data points for TCE and cis-1,2-DCE are averages of the field and lab results.

Figure 4-37. VOC Trends for IRZ-1 Showing Both Laboratory and Field-Generated Data

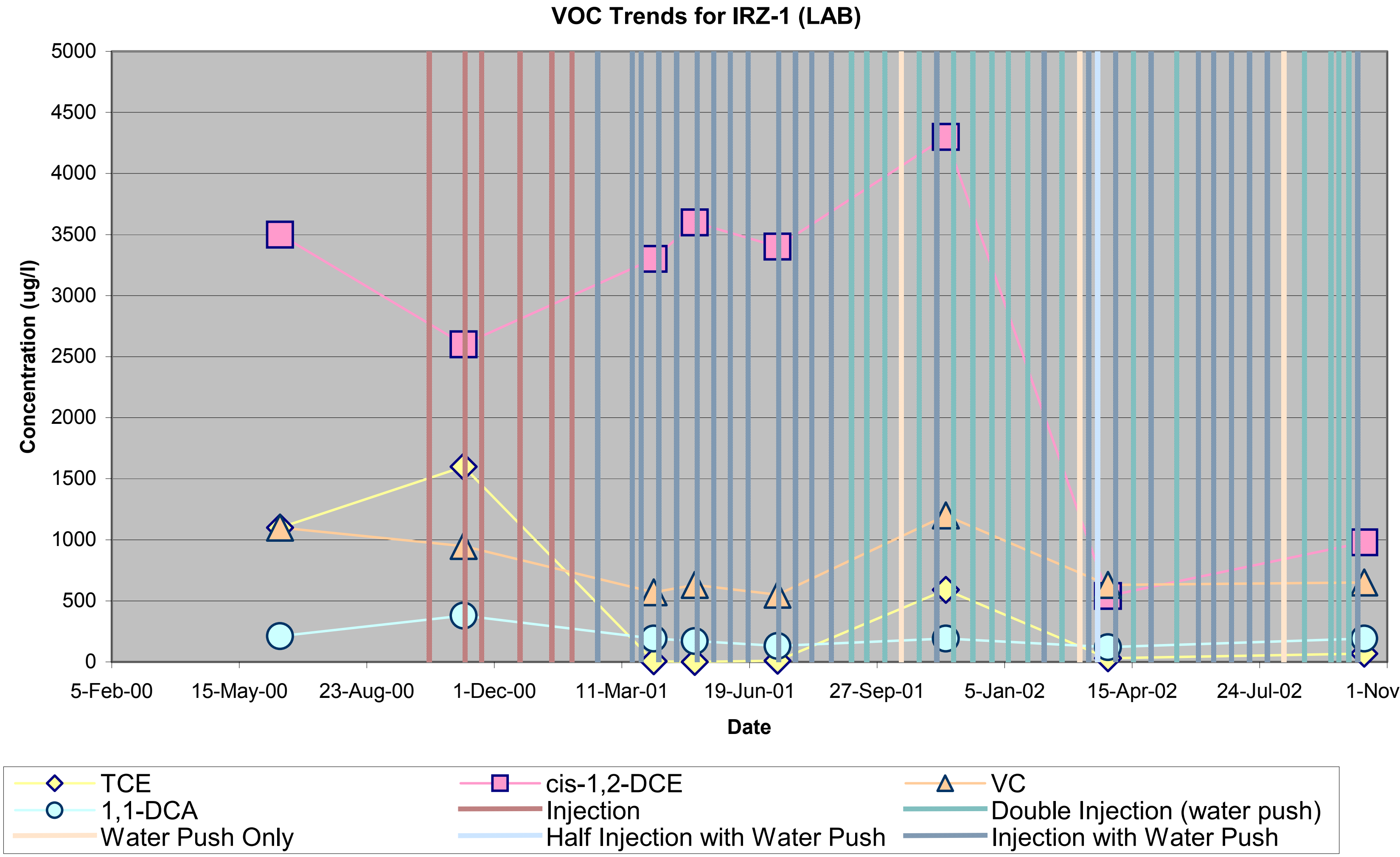


Figure 4-38. VOC Trends for IRZ-1 (Lab)

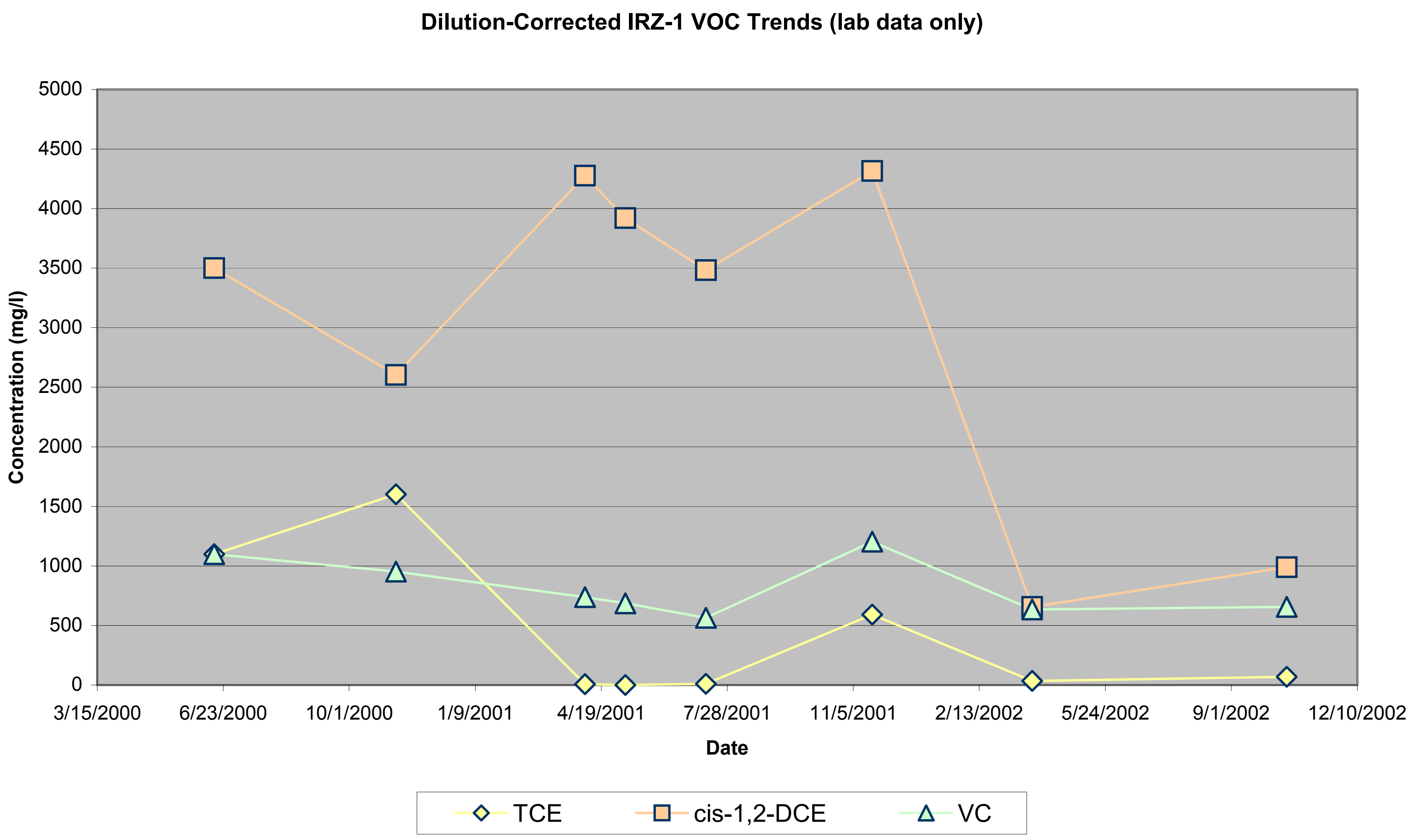
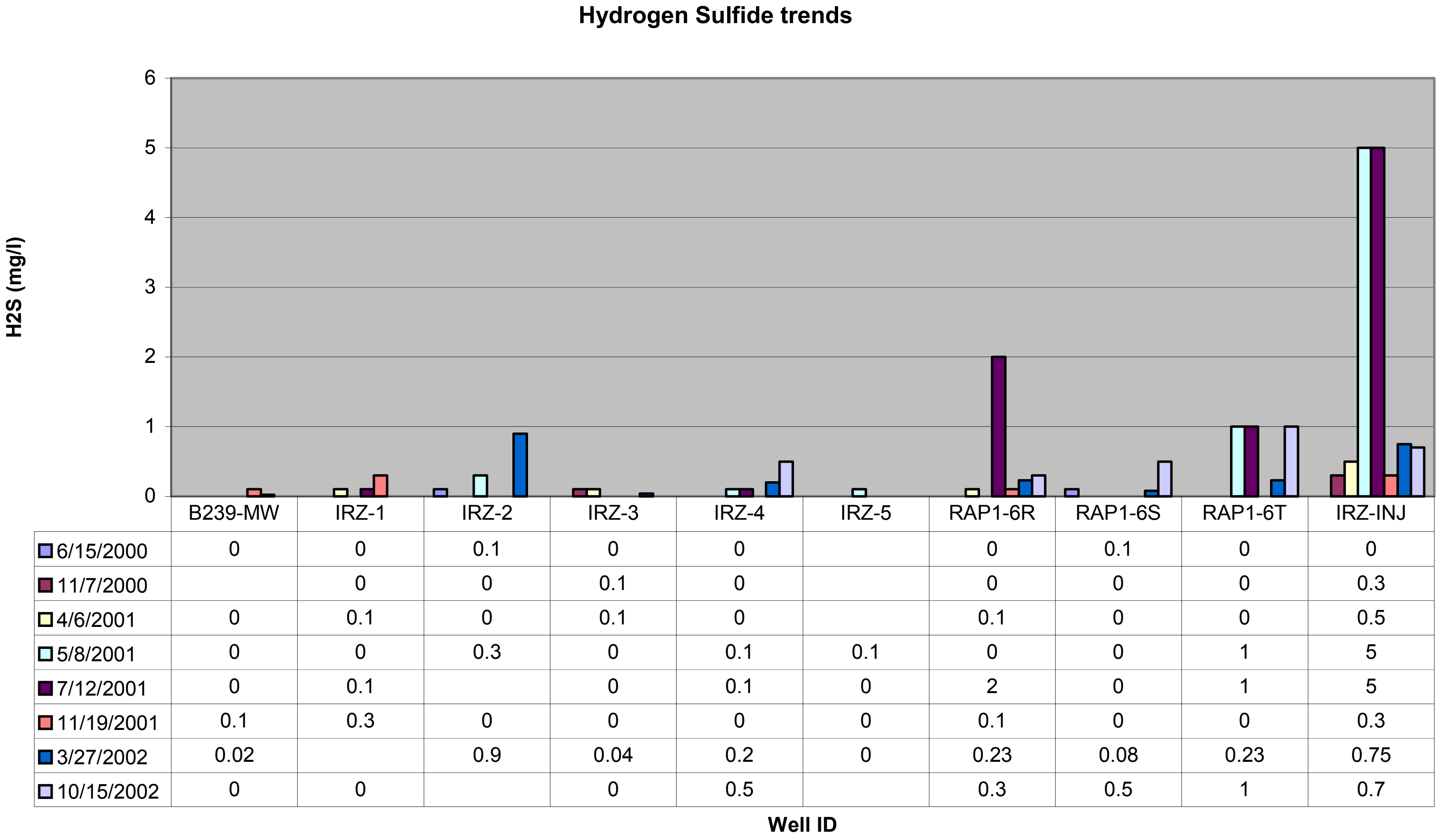


Figure 4-39. Dilution-Corrected IRZ-1 VOC Trends (Lab Data Only)



	B239-MW	IRZ-1	IRZ-2	IRZ-3	IRZ-4	IRZ-5	RAP1-6R	RAP1-6S	RAP1-6T	IRZ-INJ
6/15/2000	0	0	0.1	0	0		0	0.1	0	0
11/7/2000		0	0	0.1	0		0	0	0	0.3
4/6/2001	0	0.1	0	0.1	0		0.1	0	0	0.5
5/8/2001	0	0	0.3	0	0.1	0.1	0	0	1	5
7/12/2001	0	0.1		0	0.1	0	2	0	1	5
11/19/2001	0.1	0.3	0	0	0	0	0.1	0	0	0.3
3/27/2002	0.02		0.9	0.04	0.2	0	0.23	0.08	0.23	0.75
10/15/2002	0	0		0	0.5		0.3	0.5	1	0.7

Figure 4-40. Hydrogen Sulfide Trends

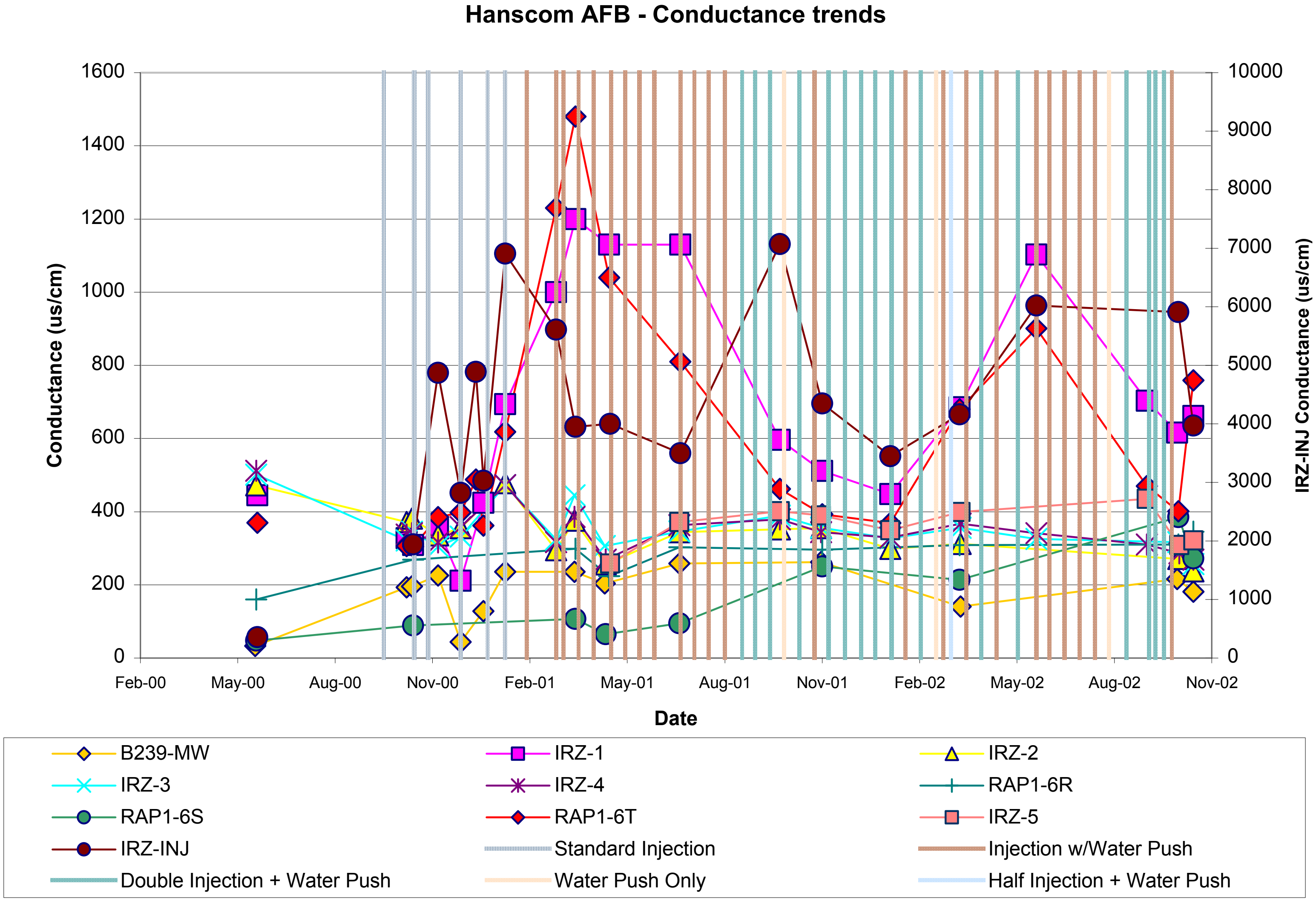


Figure 4-41-(a) Conductance Trends vs. Time, Showing All Data and Injection Events

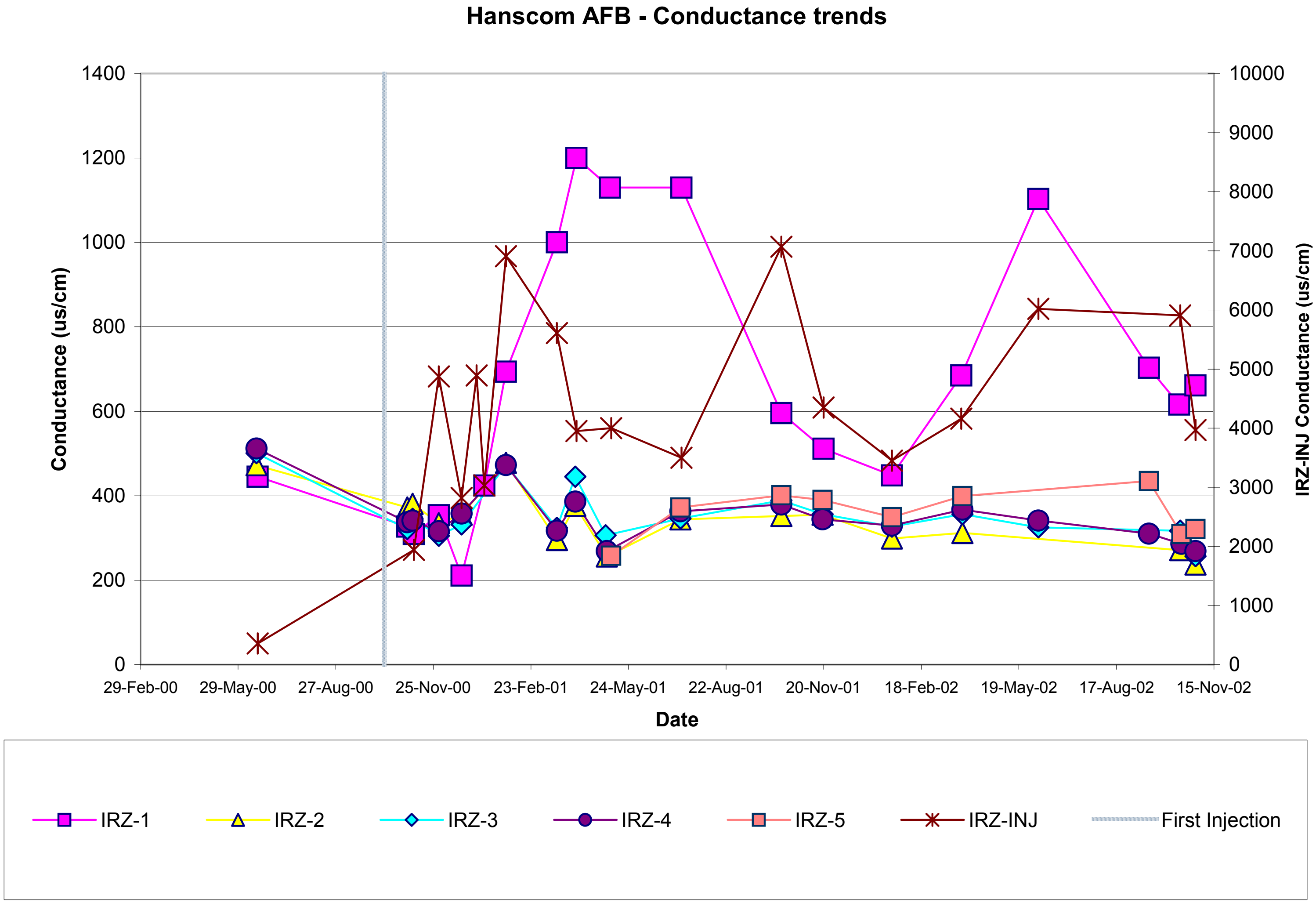


Figure 4-41-(b) Conductance Trends vs. Time, "IRZ" Labeled Wells Only

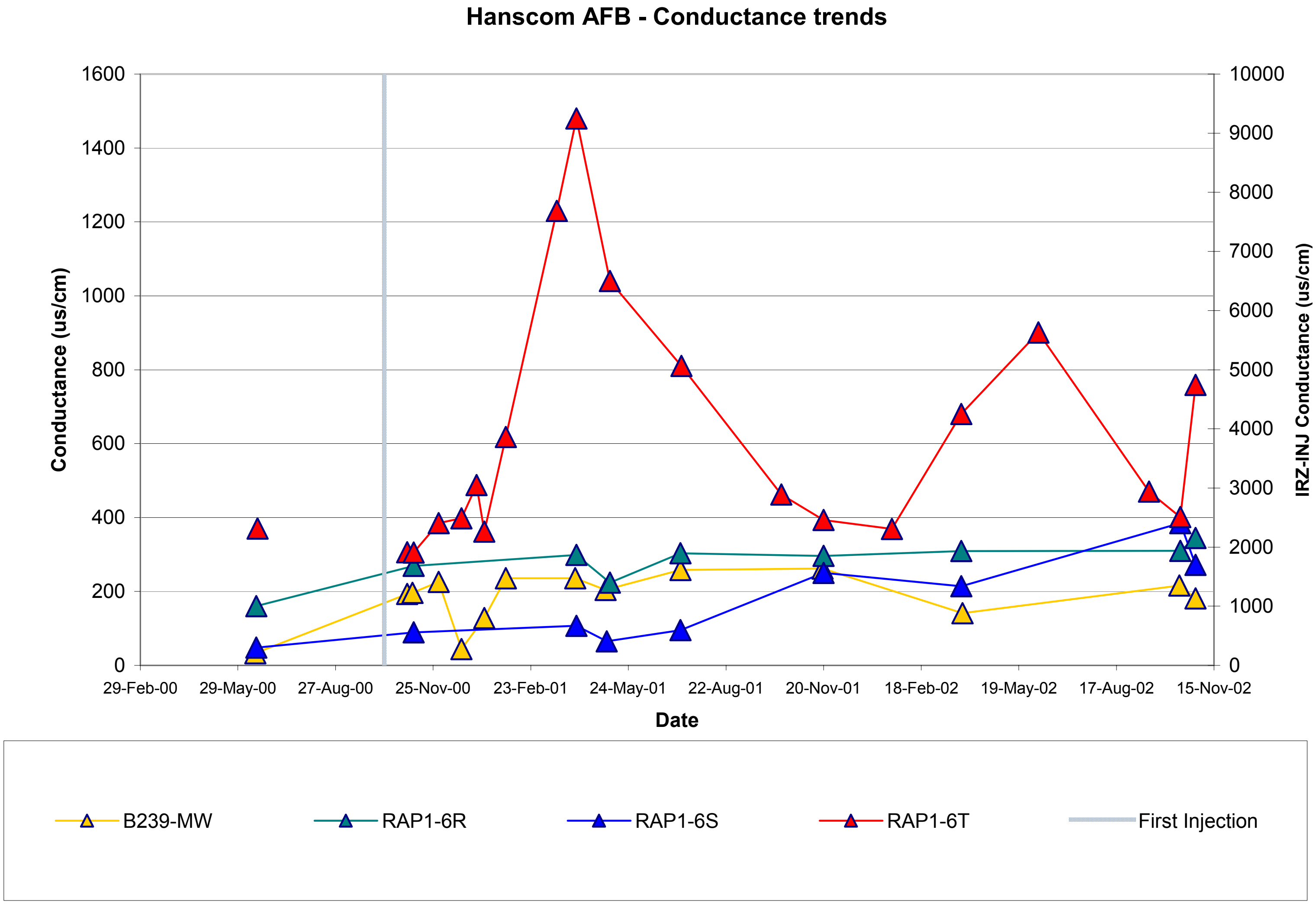


Figure 4-41-(c) Conductance Trends vs. Time, "RAP and B" Labeled Wells Only

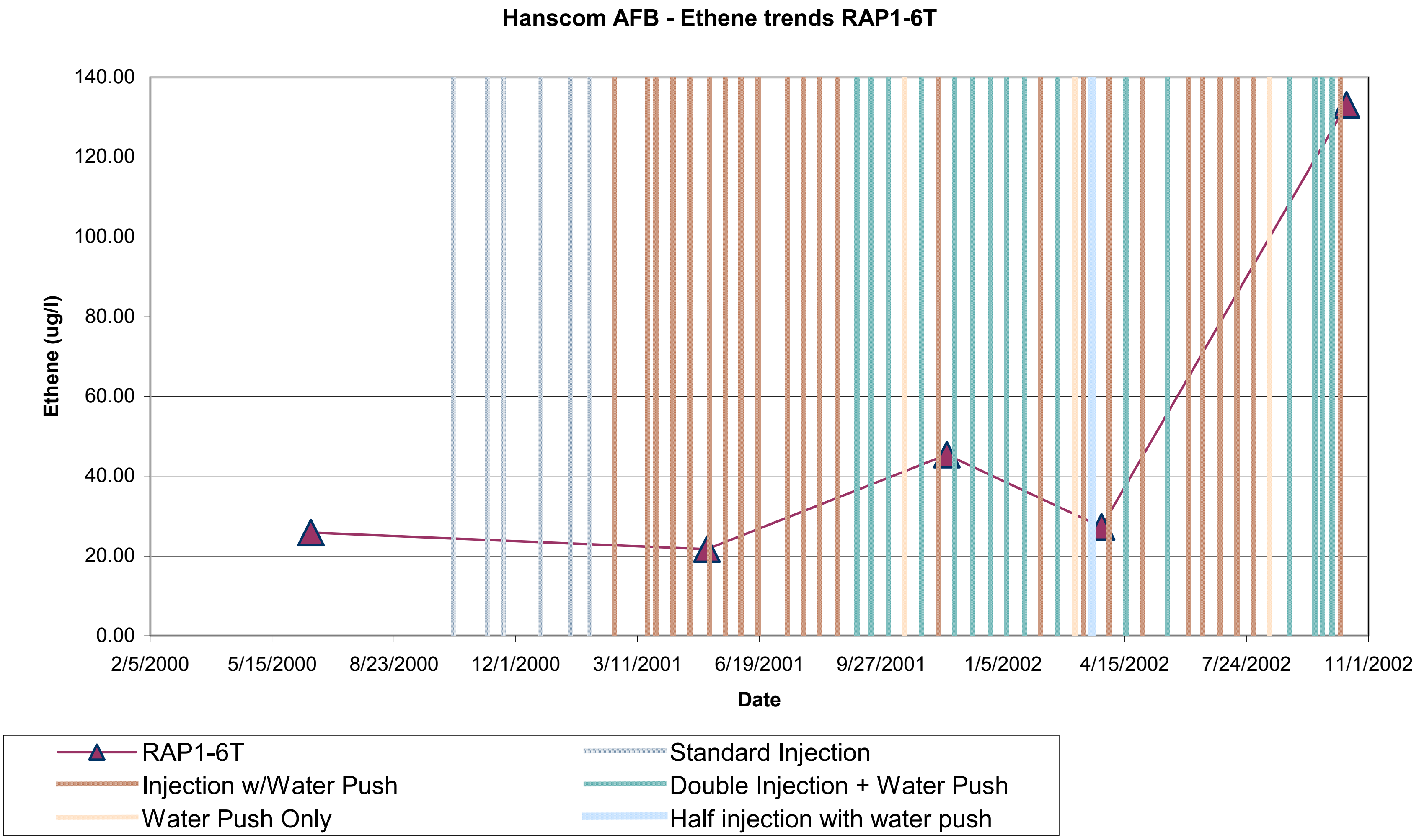


Figure 4-42. Ethene Trends RAP1-6T

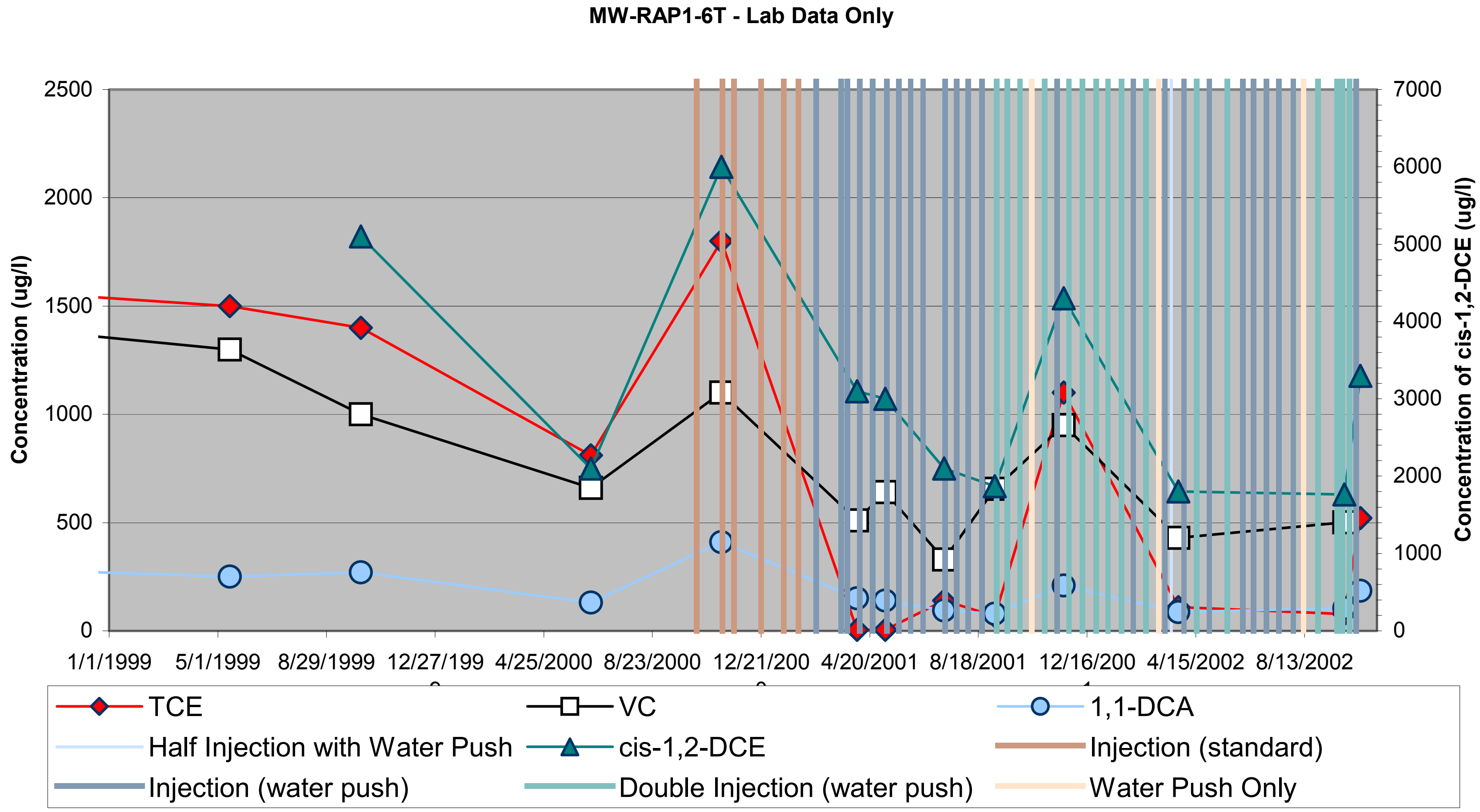


Figure 4-43. Recent VOC Trends for MW-RAP1-6T – Lab Data Only

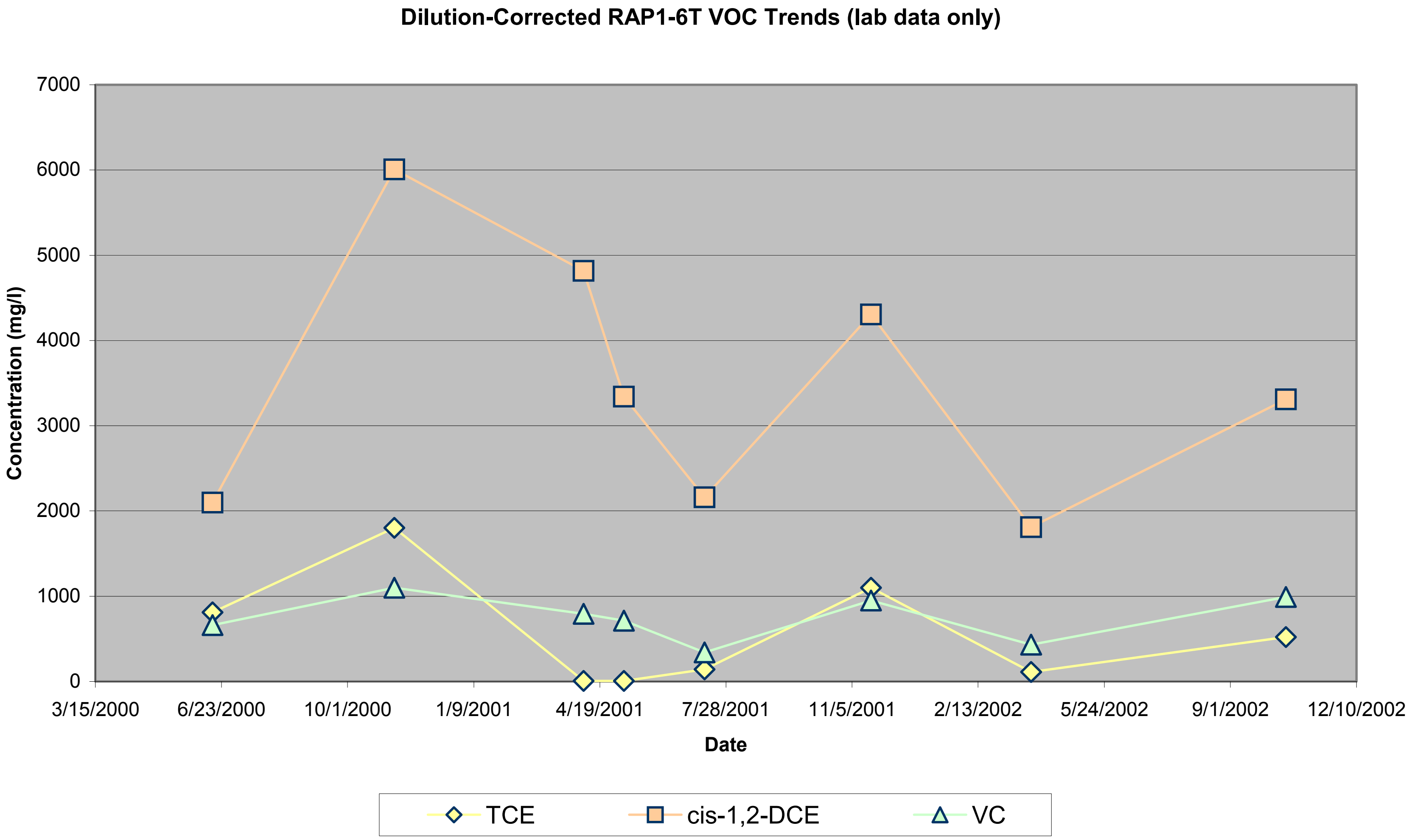


Figure 4-44. Dilution-Corrected RAP1-6T VOC Trends (Lab Data Only)

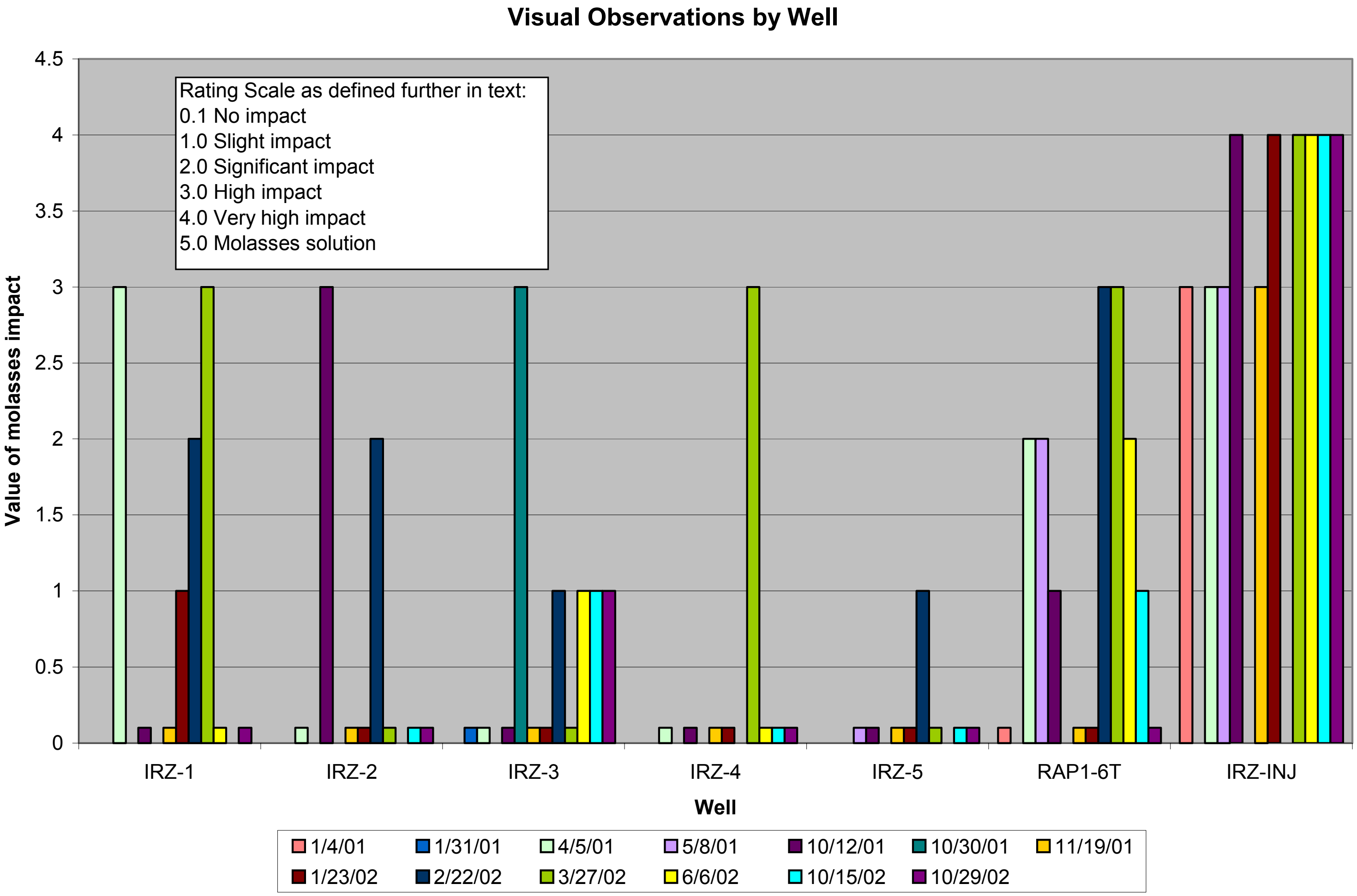


Figure 4-45. Qualitative Observation Ratings of Samples Taken from Demonstration Area Wells Over Time

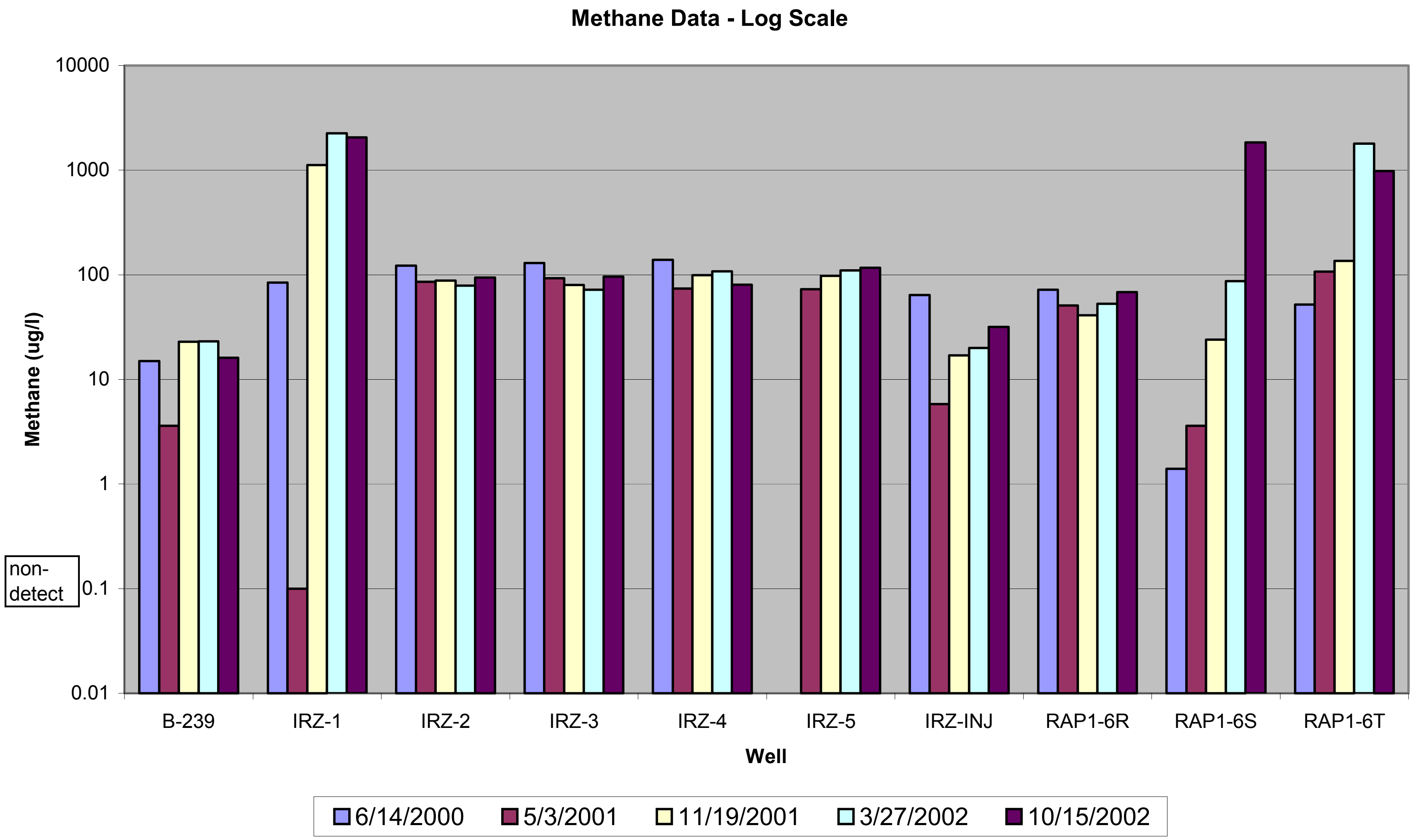


Figure 4-46. Methane Measurements from Demonstration Area Wells Over Time

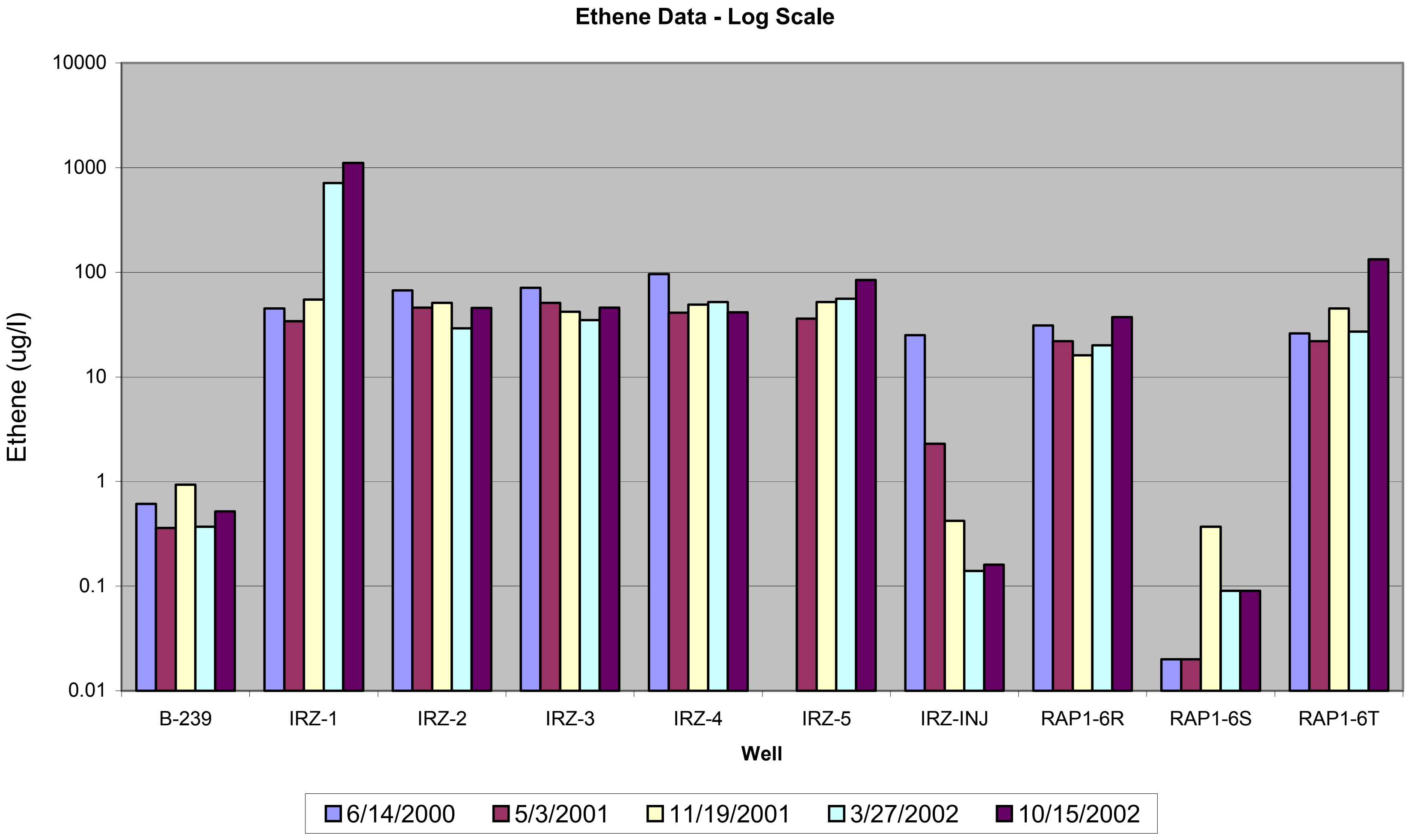


Figure 4-47. Ethene Measurements from Demonstration Area Wells Over Time

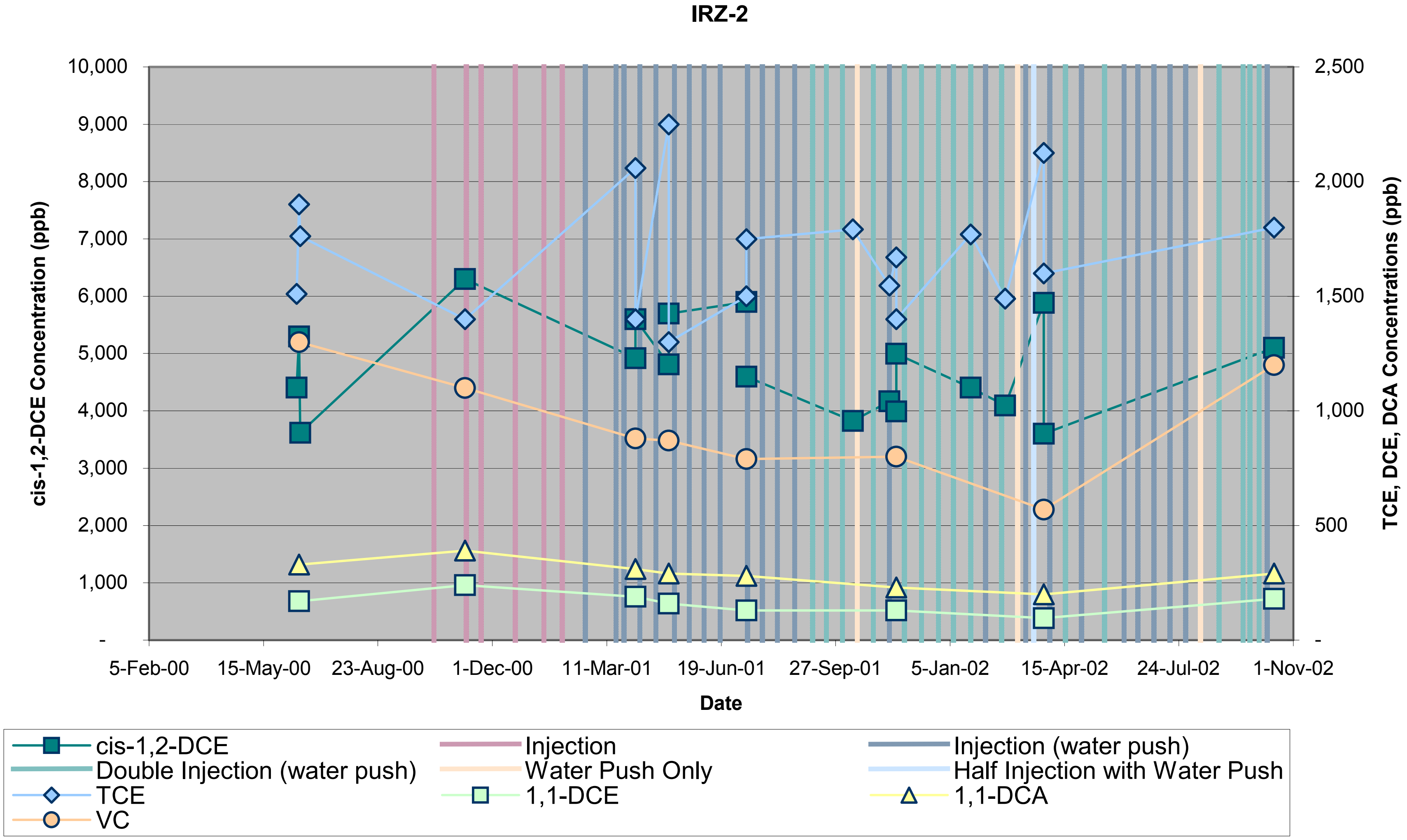


Figure 4-48. VOC Trends for IRZ-2 Showing Both Laboratory and Field-Generated Data

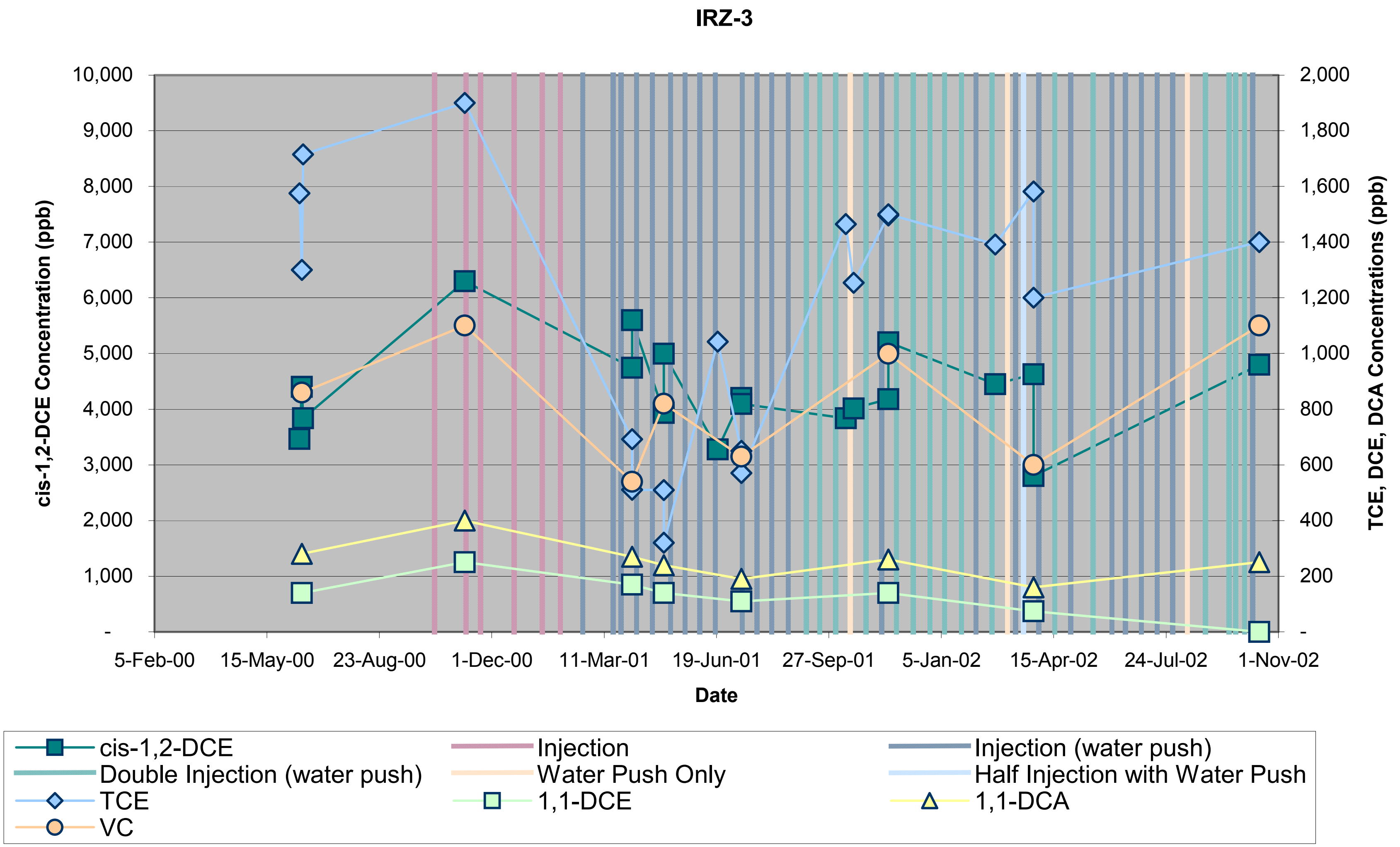


Figure 4-49. VOC Trends for IRZ-3 Showing Both Laboratory and Field-Generated Data

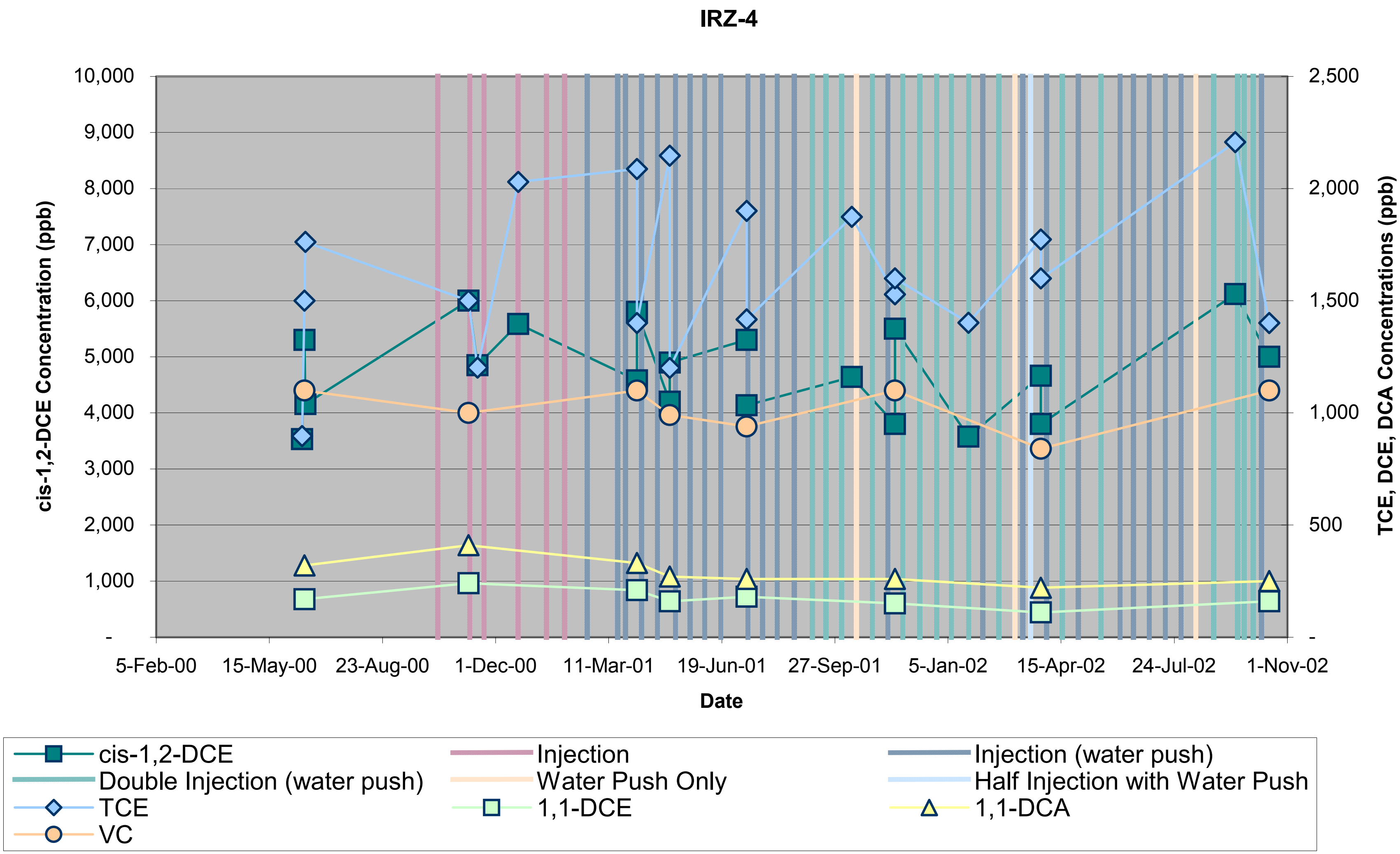


Figure 4-50. VOC Trends for IRZ-4 Showing Both Laboratory and Field-Generated Data

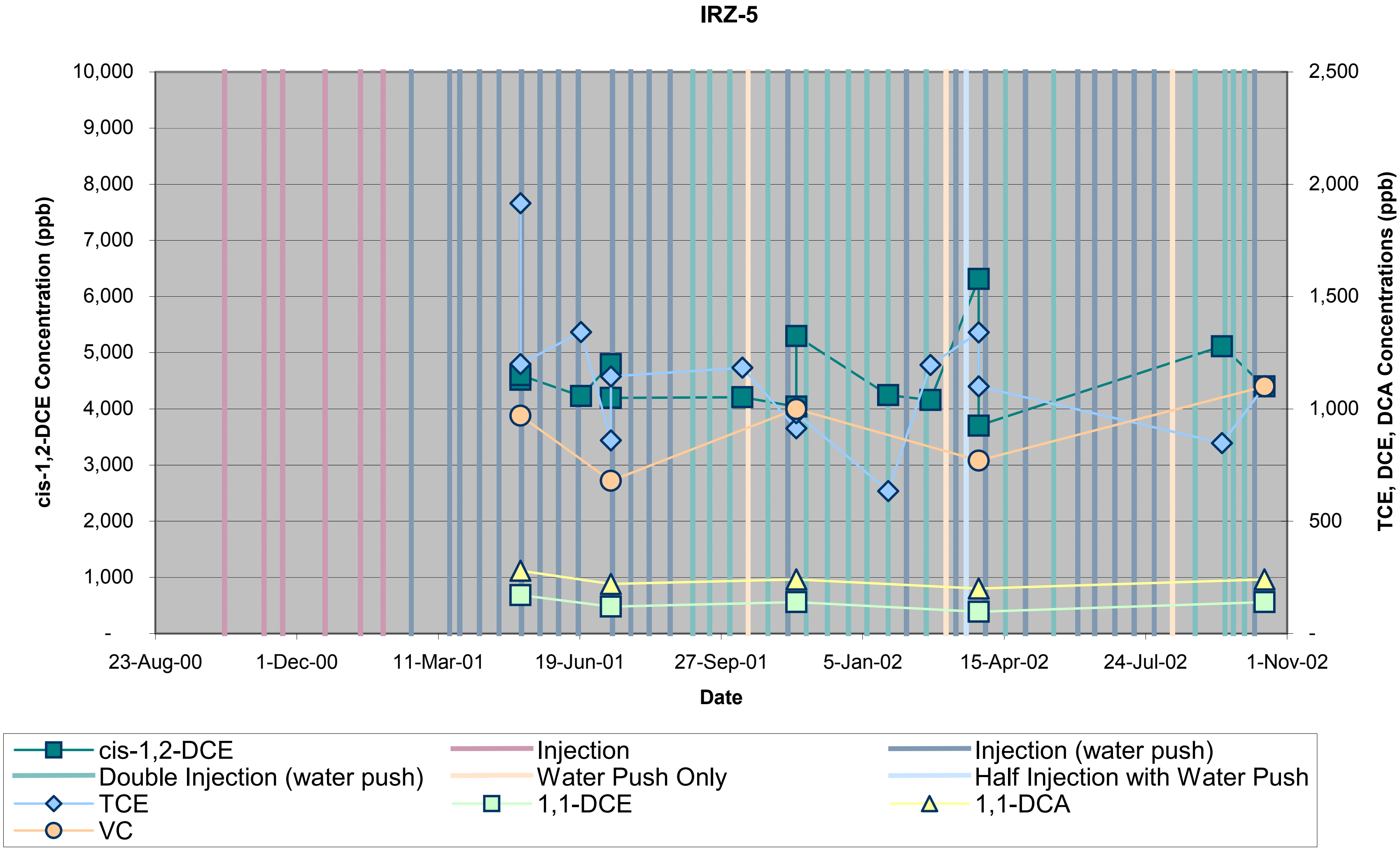


Figure 4-51. Trends for IRZ-5 Showing Both Laboratory and Field-Generated Data

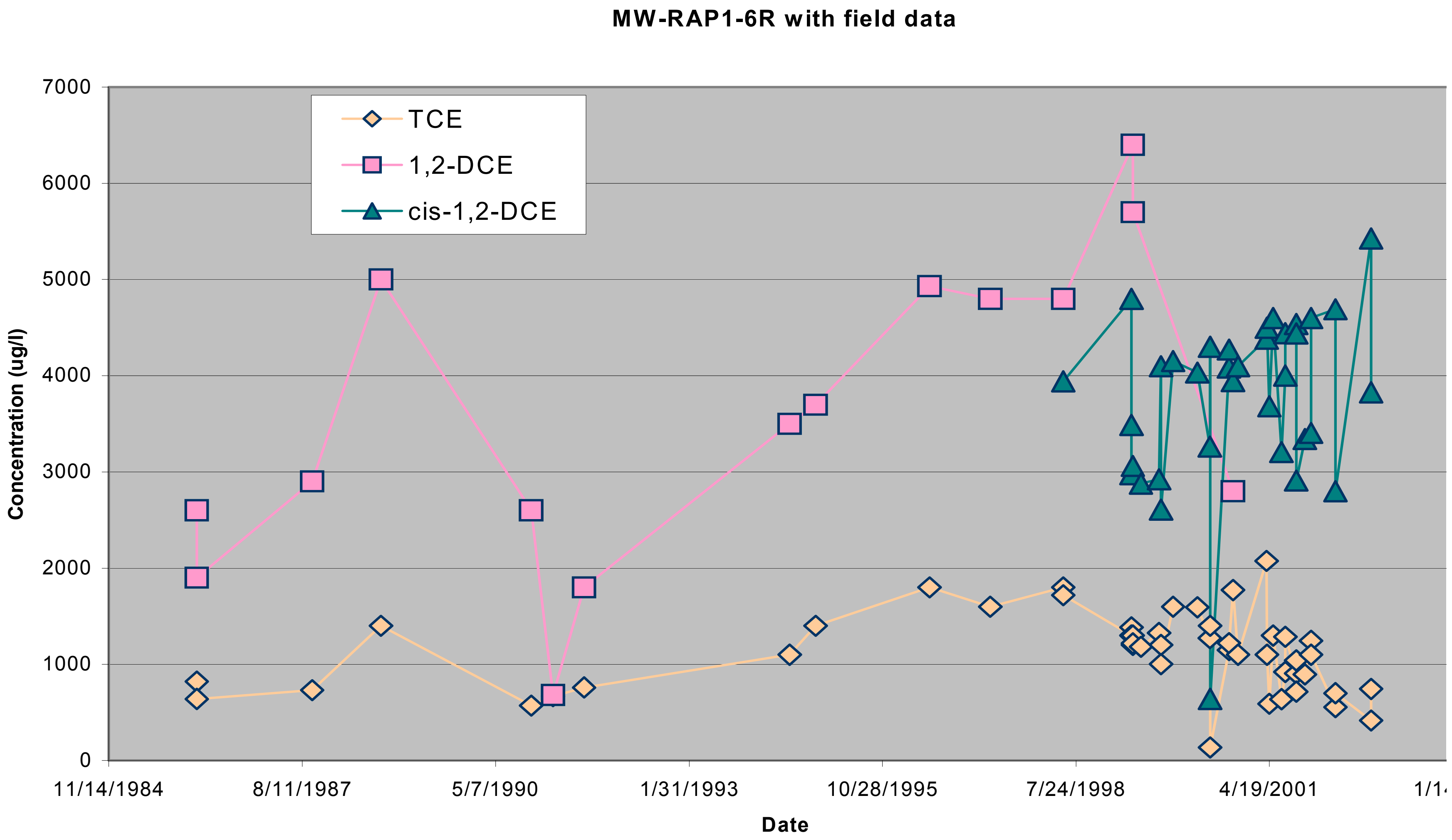


Figure 4-52. Historical VOC Trends for RAP1-6R, Laboratory and Field-Generated Data

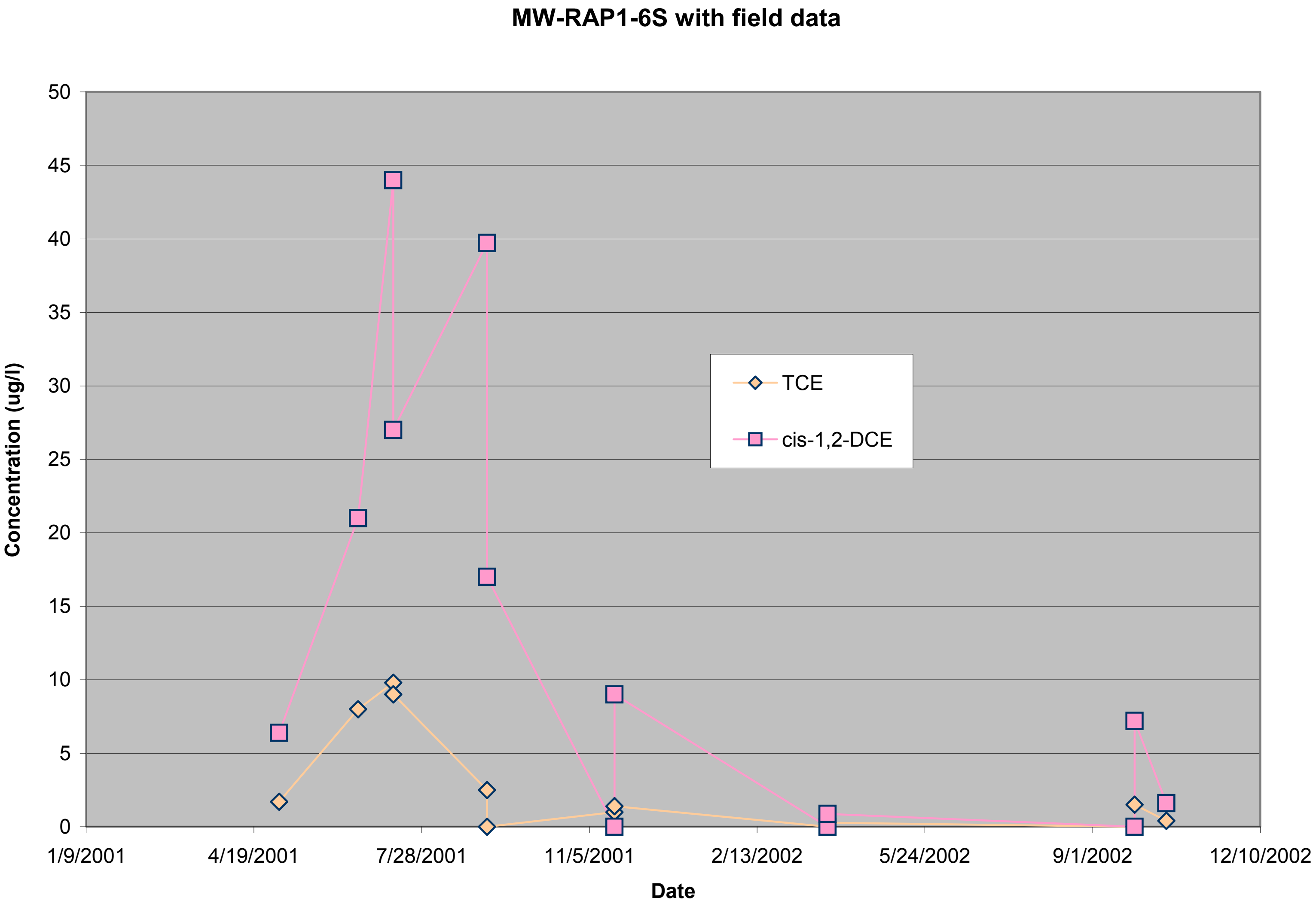


Figure 4-53. Recent VOC Trends for RAP1-6S Showing Both Laboratory and Field-Generated Data

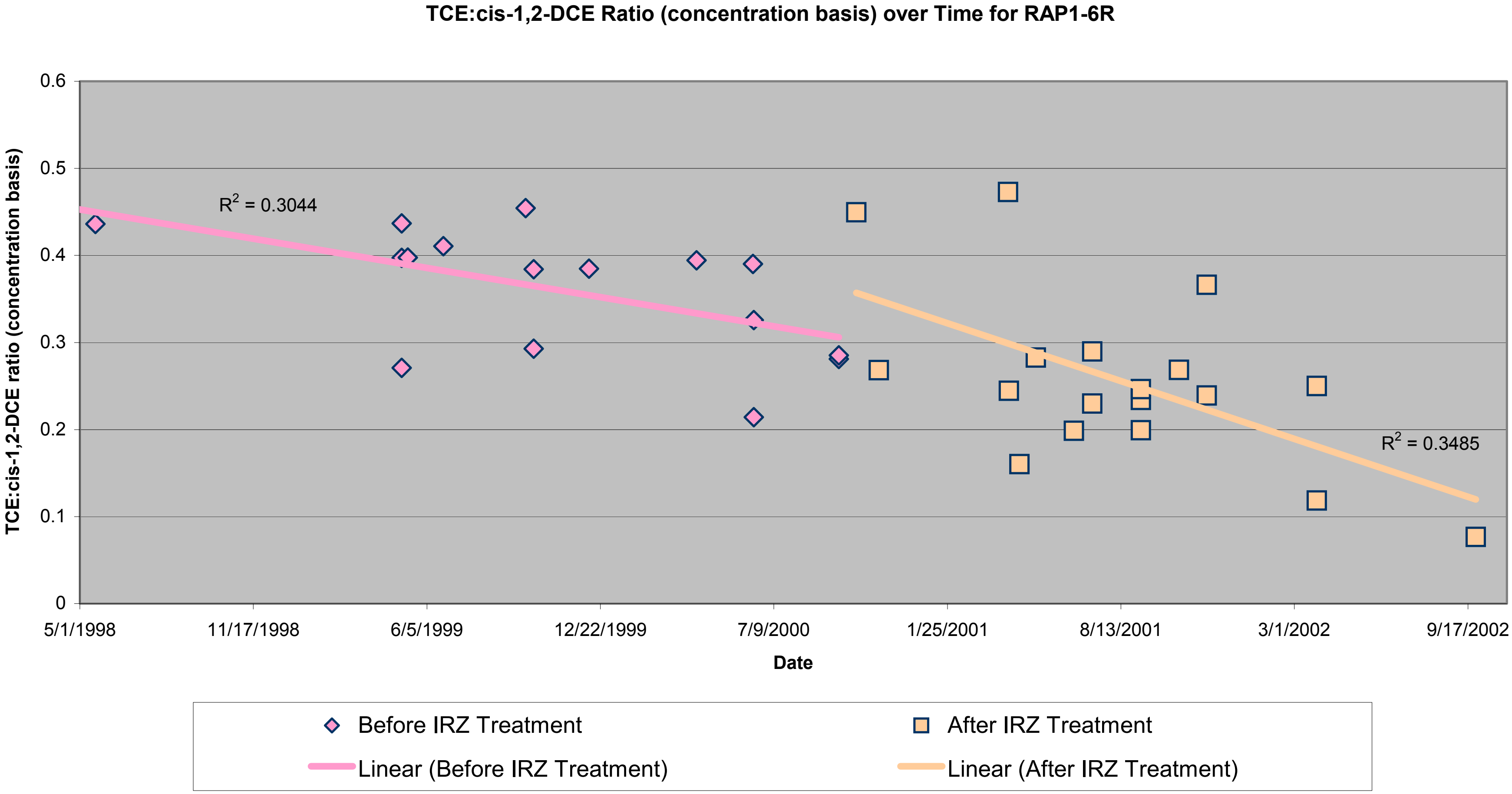


Figure 4-54. TCE:cis-1,2-DCE Ratio (Concentration Basis) over Time for RAP1-6R

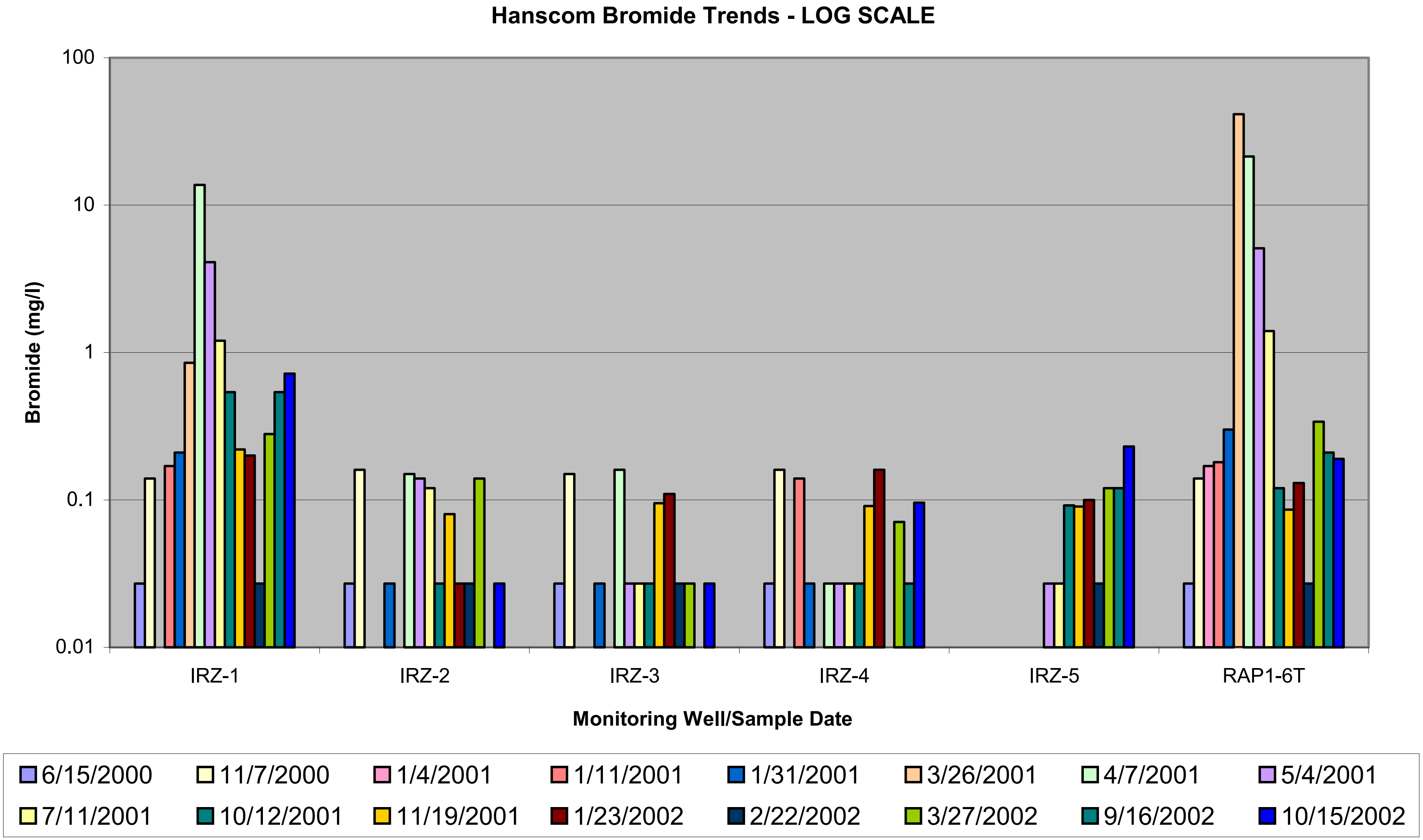


Figure 4-55. Hanscom Bromide Trends – Log Scale

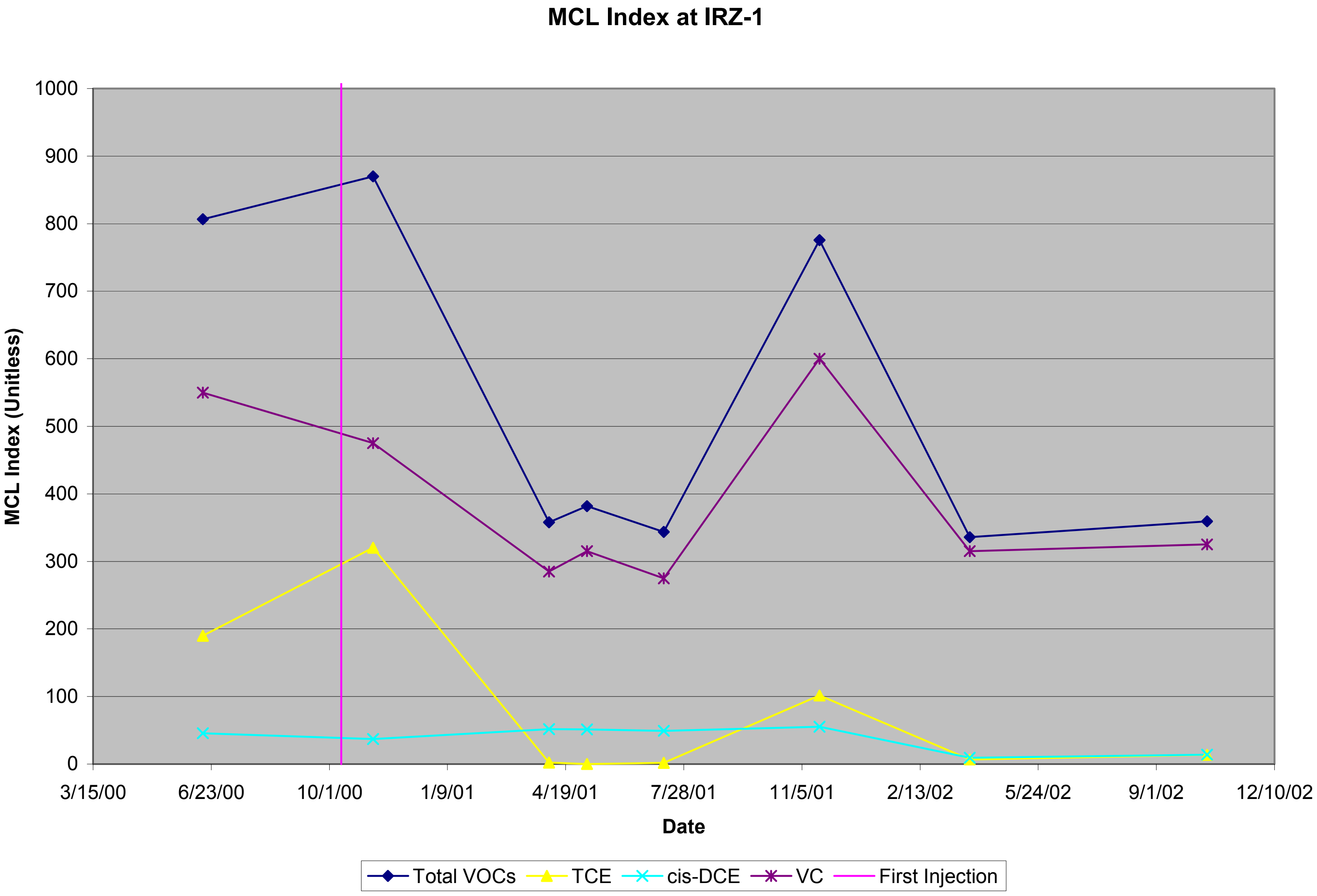


Figure 4-56. MCL Index at IRZ-1

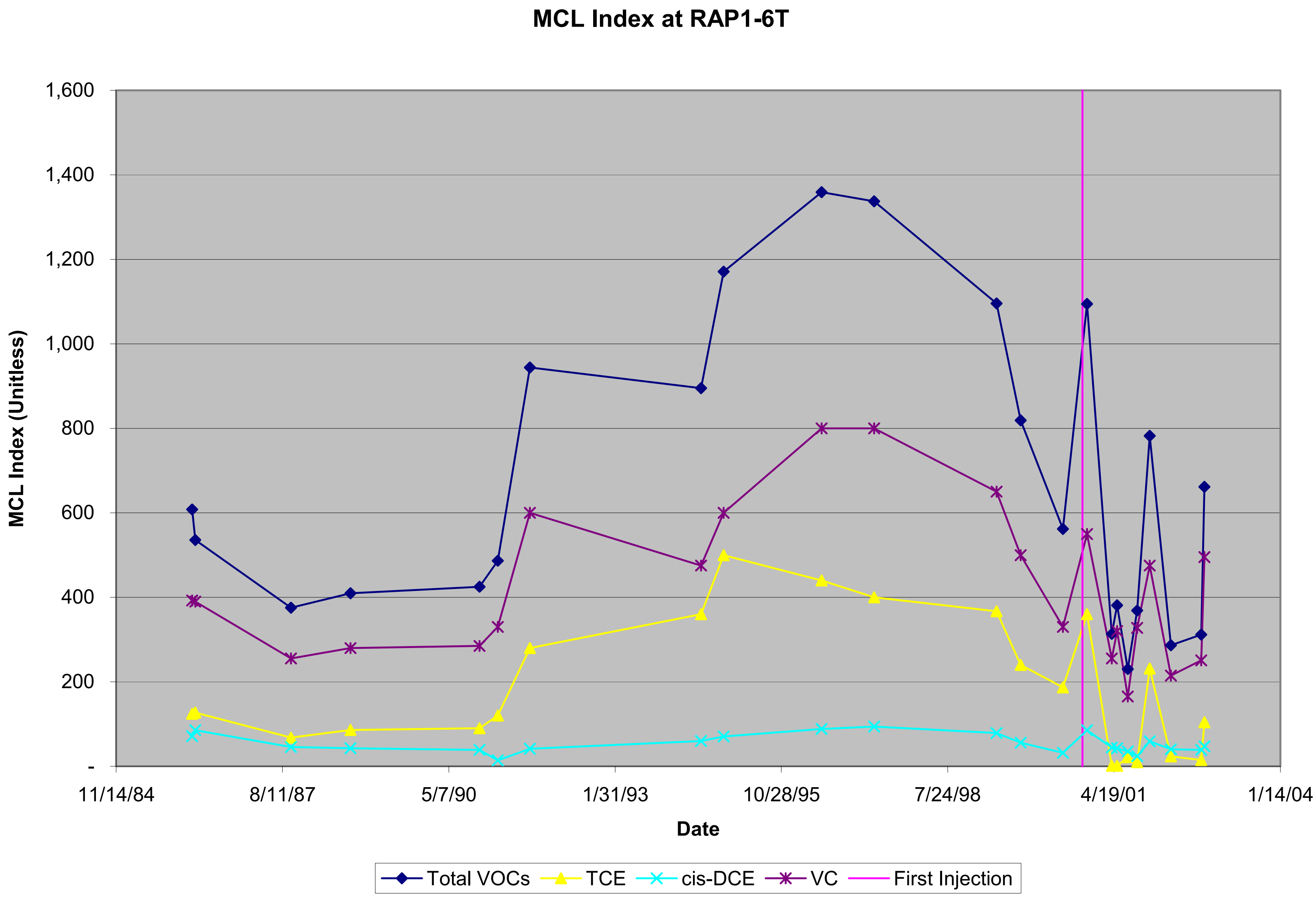


Figure 4-57. MCL Index at RAP1-6T (11-14-1984 through current)

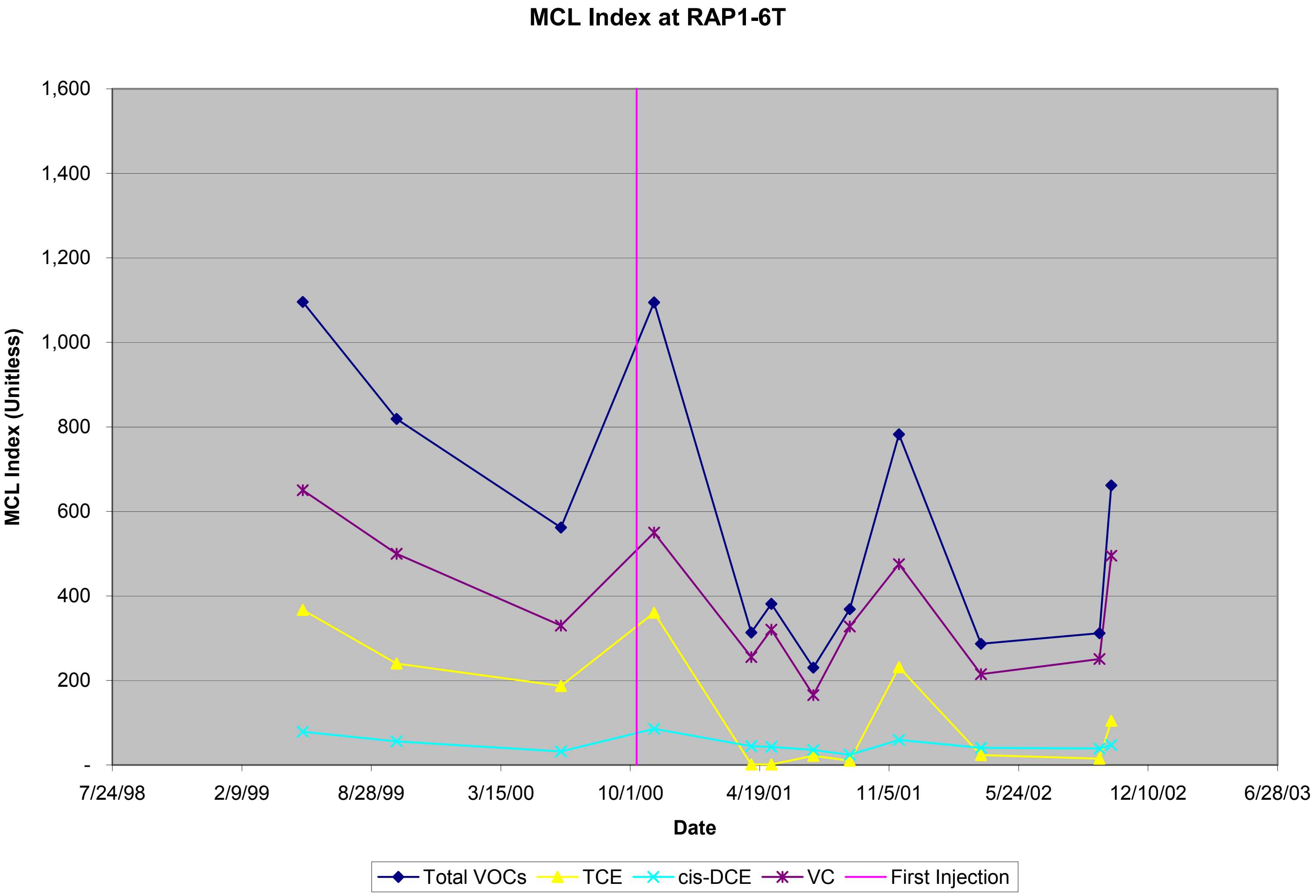


Figure 4-58. MCL Index at RAP1-6T (07-24-1998 through current)

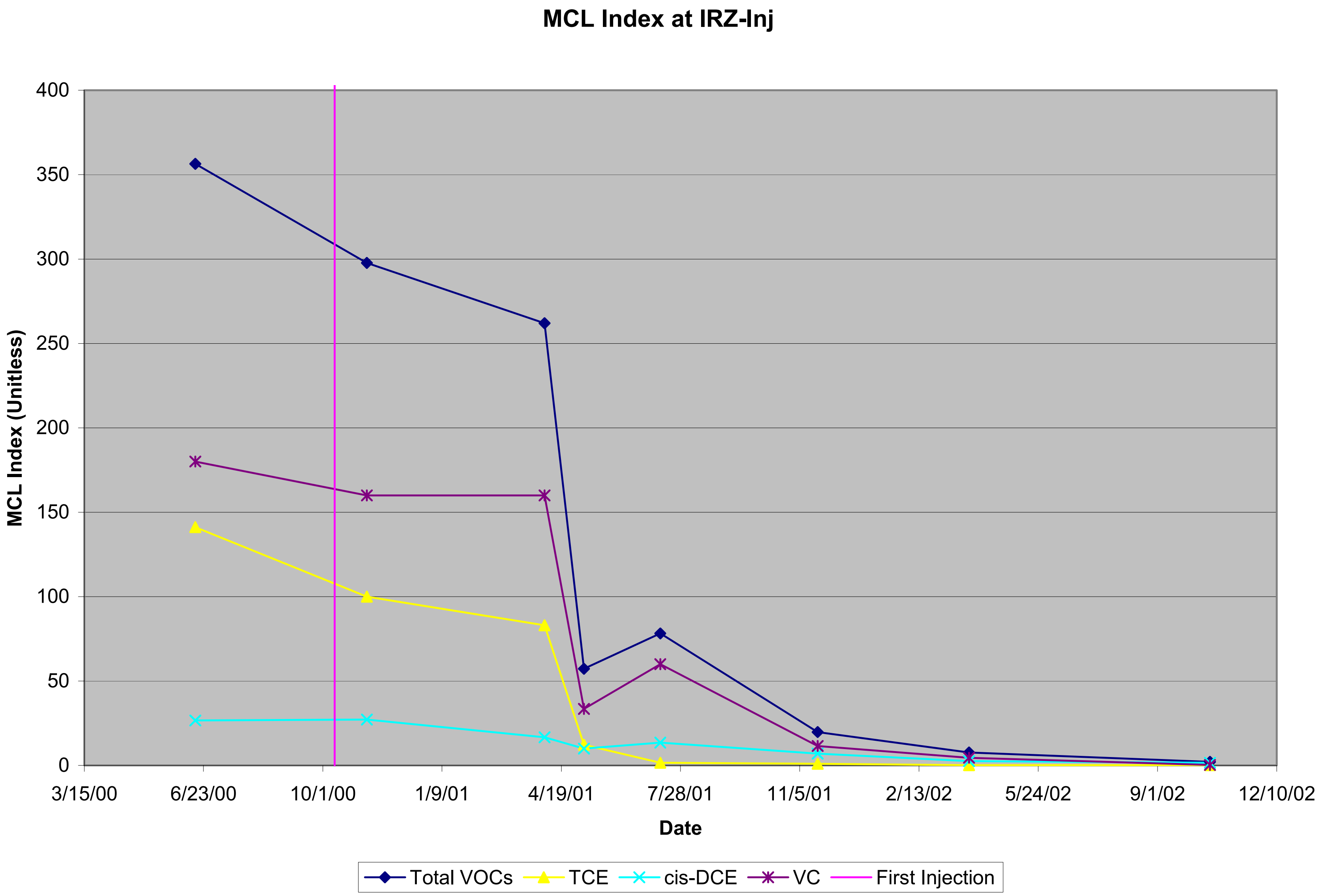


Figure 4-59. MCL Index at IRZ-INJ

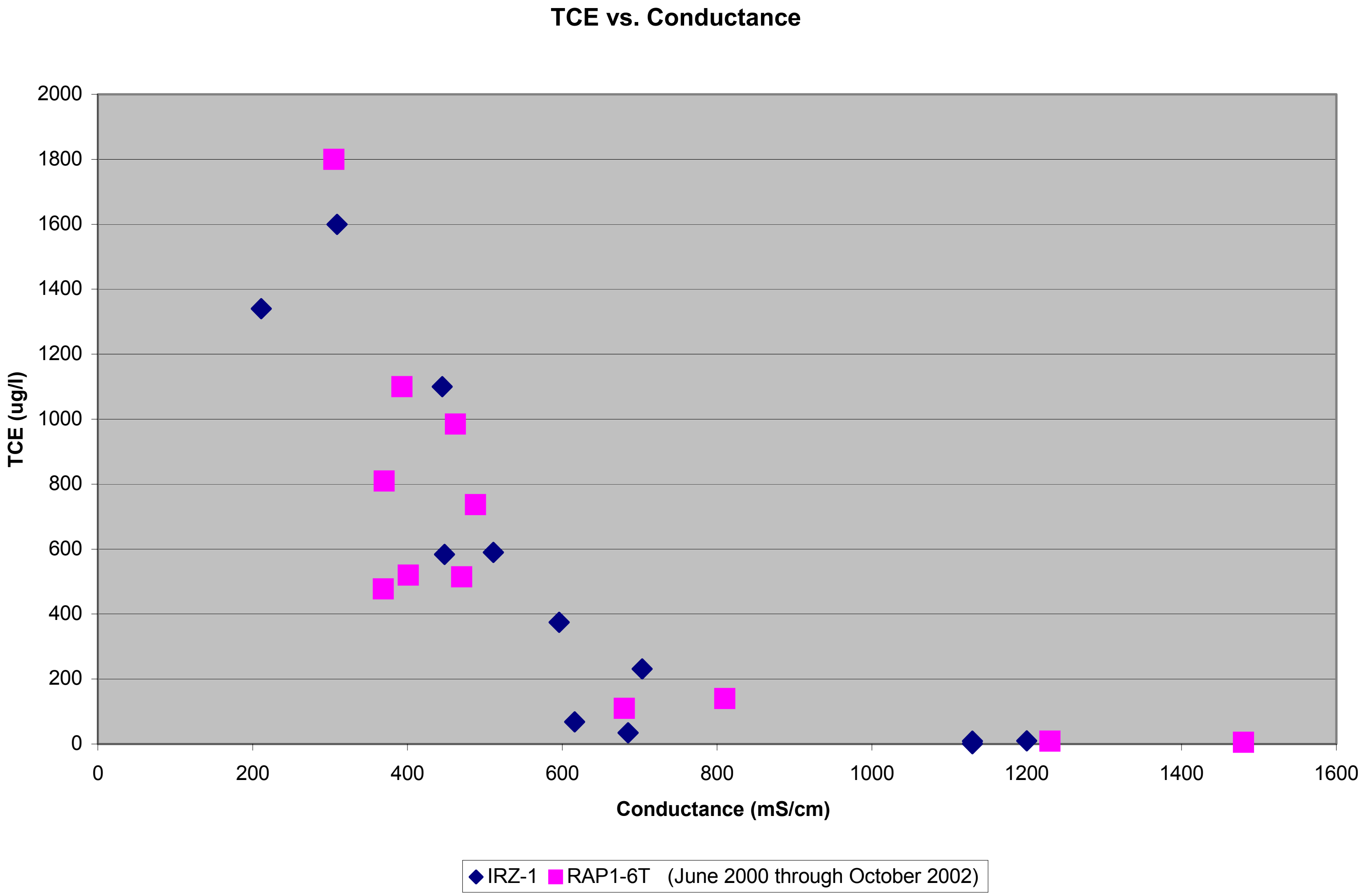


Figure 4-60. TCE vs. Conductance at IRZ-1 and RAP1-6T (June 2000 through October 2002)

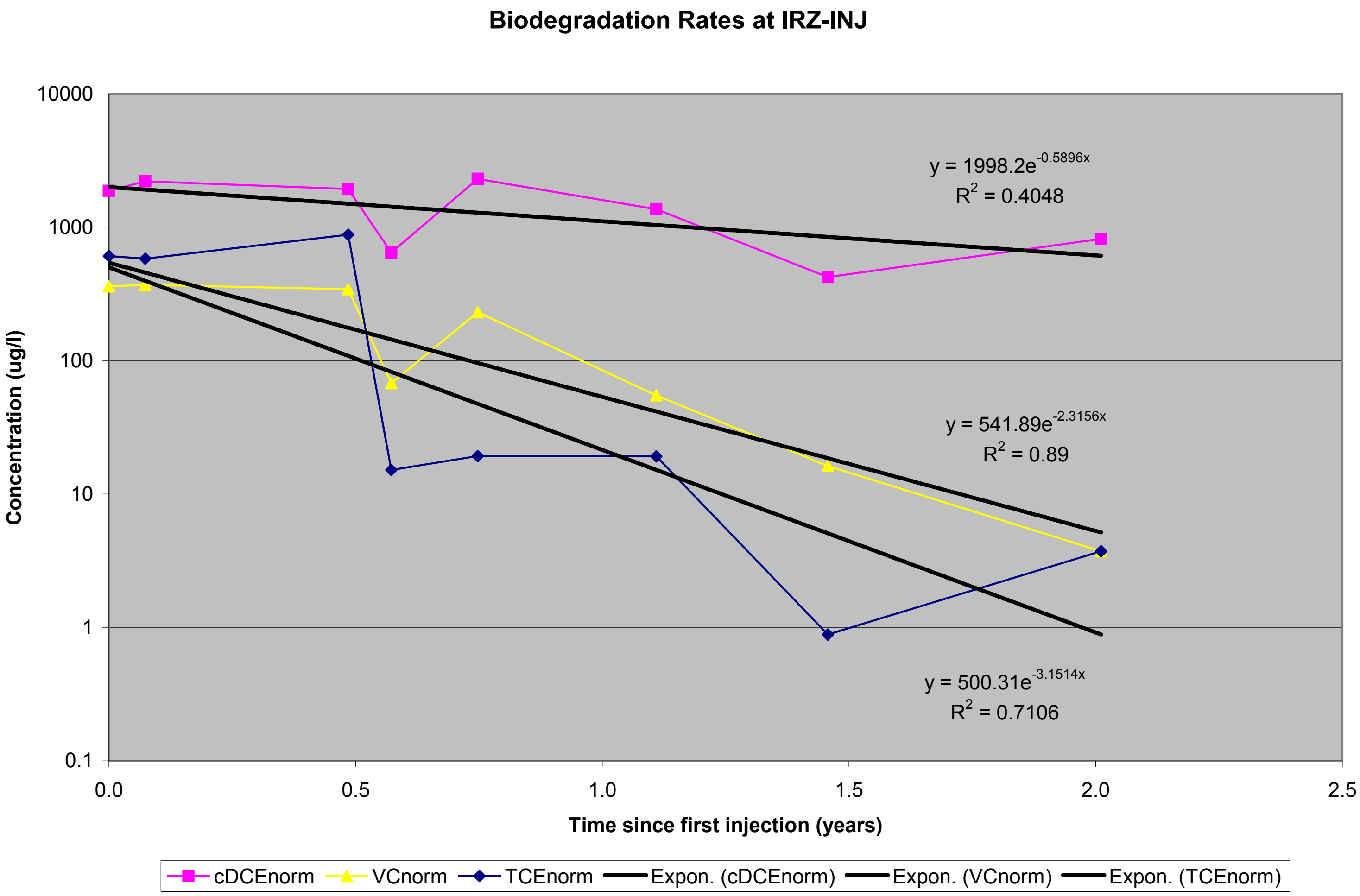


Figure 4-61. Biodegradation Rates at IRZ-INJ

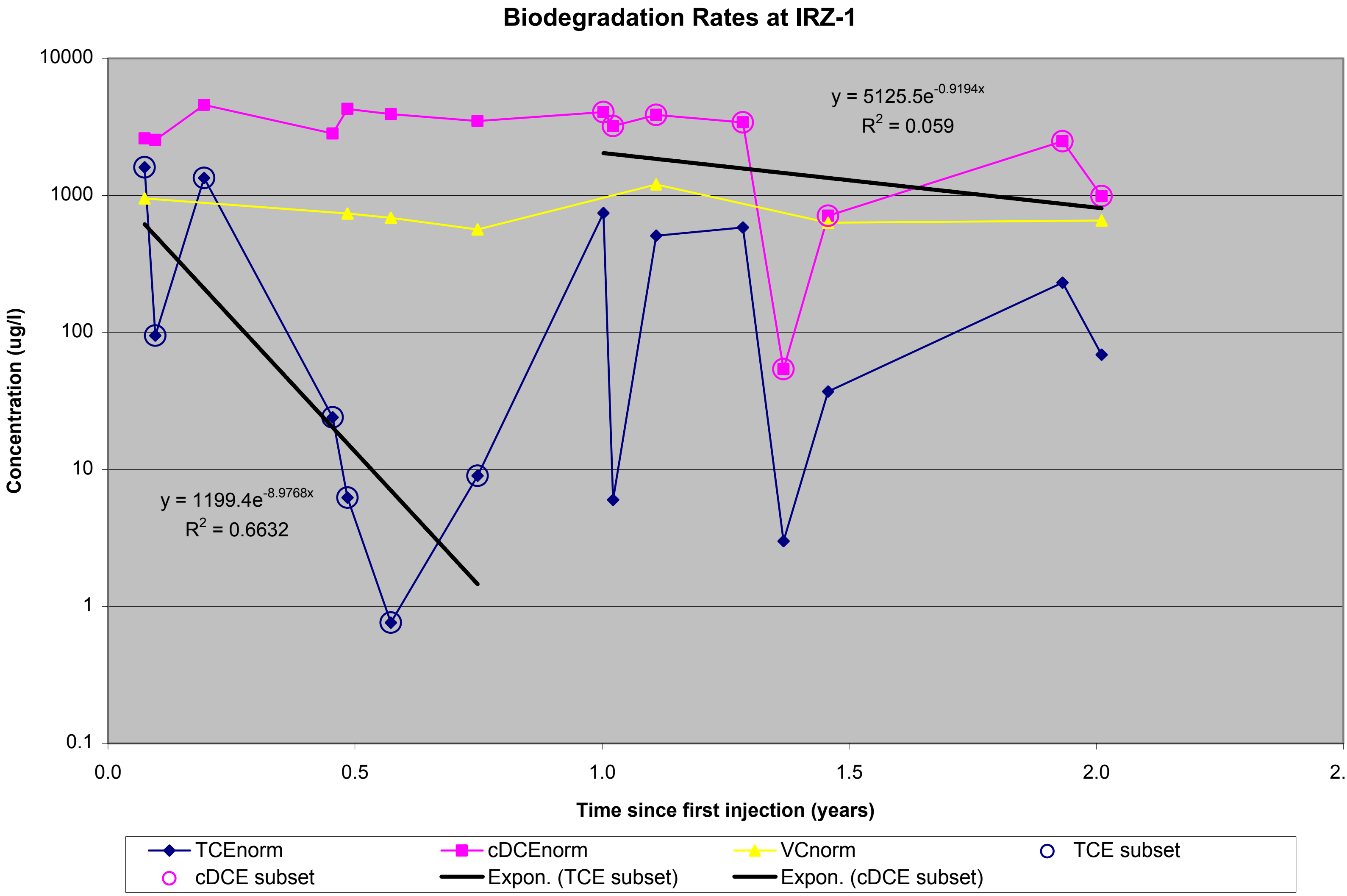


Figure 4-62. Biodegradation Rates at IRZ-1

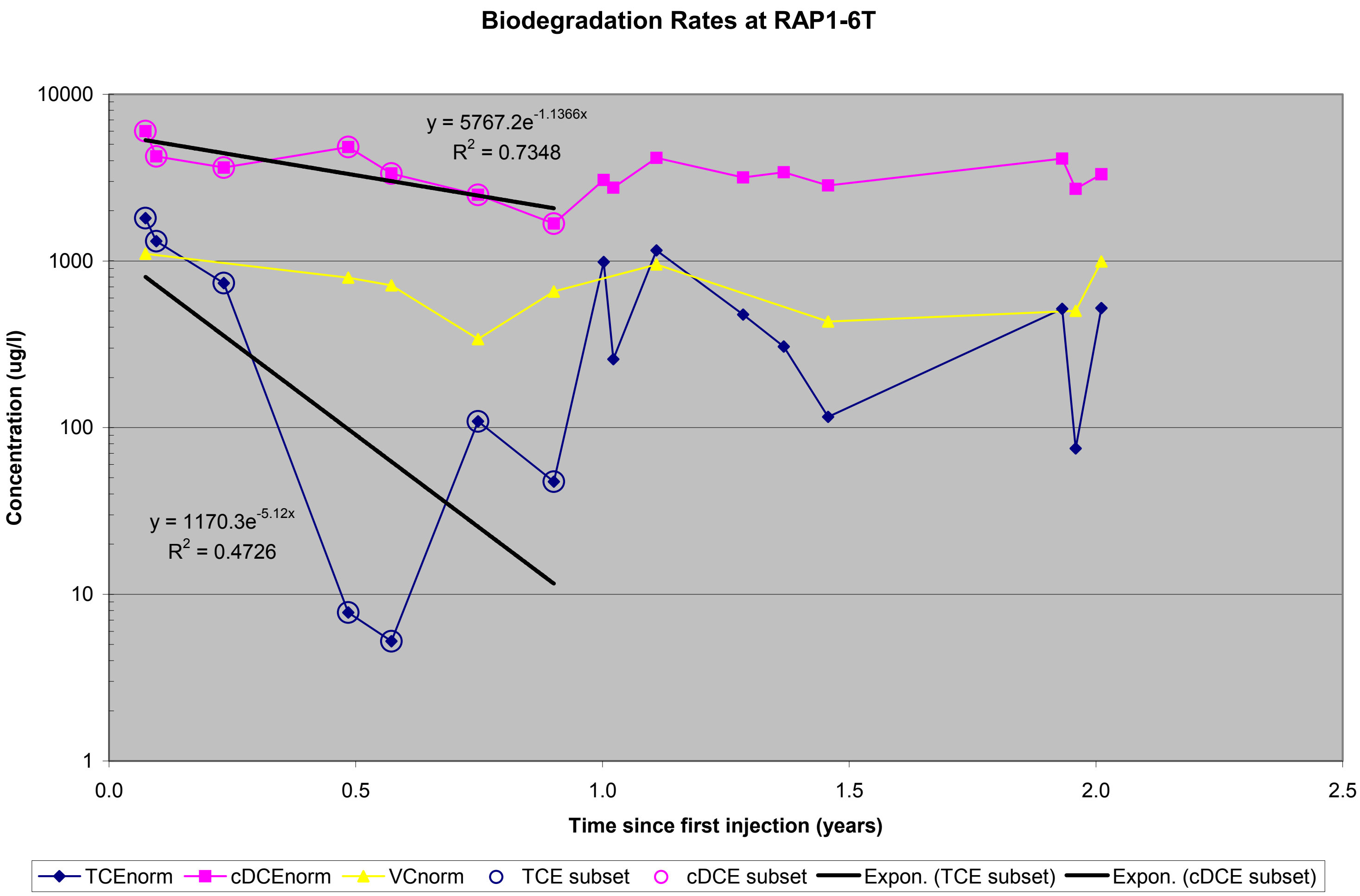


Figure 4-63. Biodegradation Rates at RAP1-6T

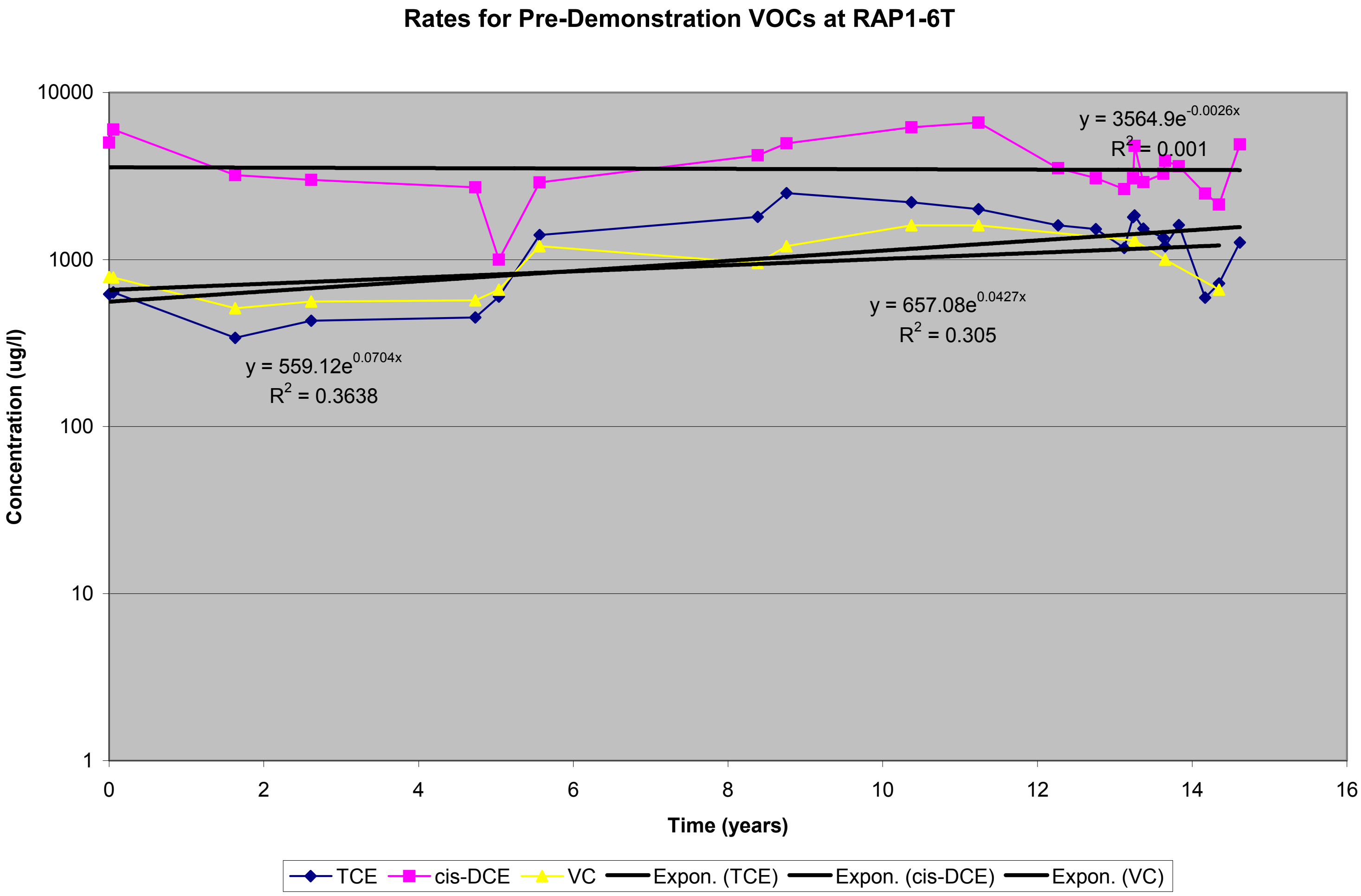


Figure 4-64. Rates for Pre-Demonstration VOCs at RAP1-6T

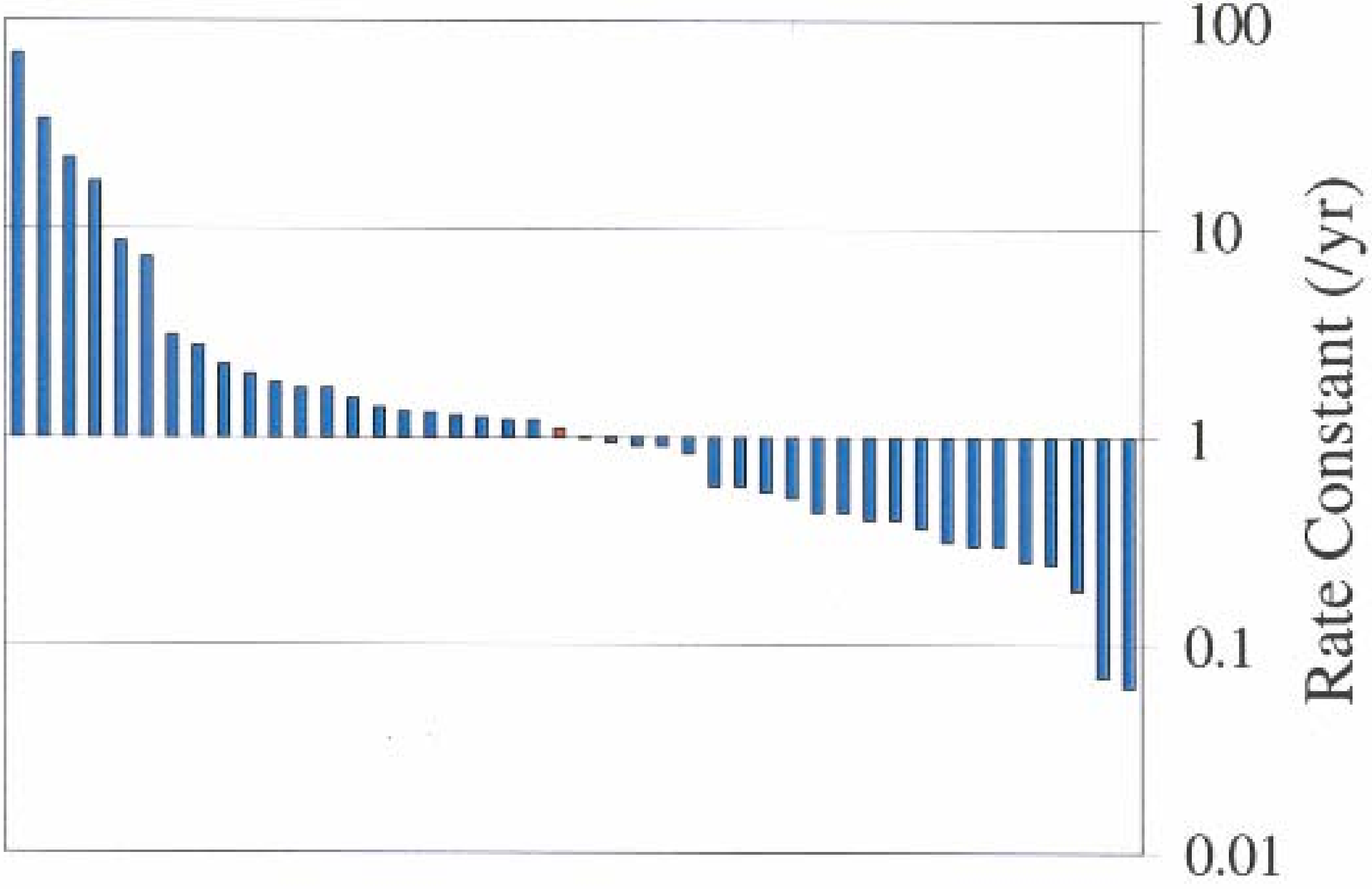


Figure 4-65. Literature Rate Constants for TCE

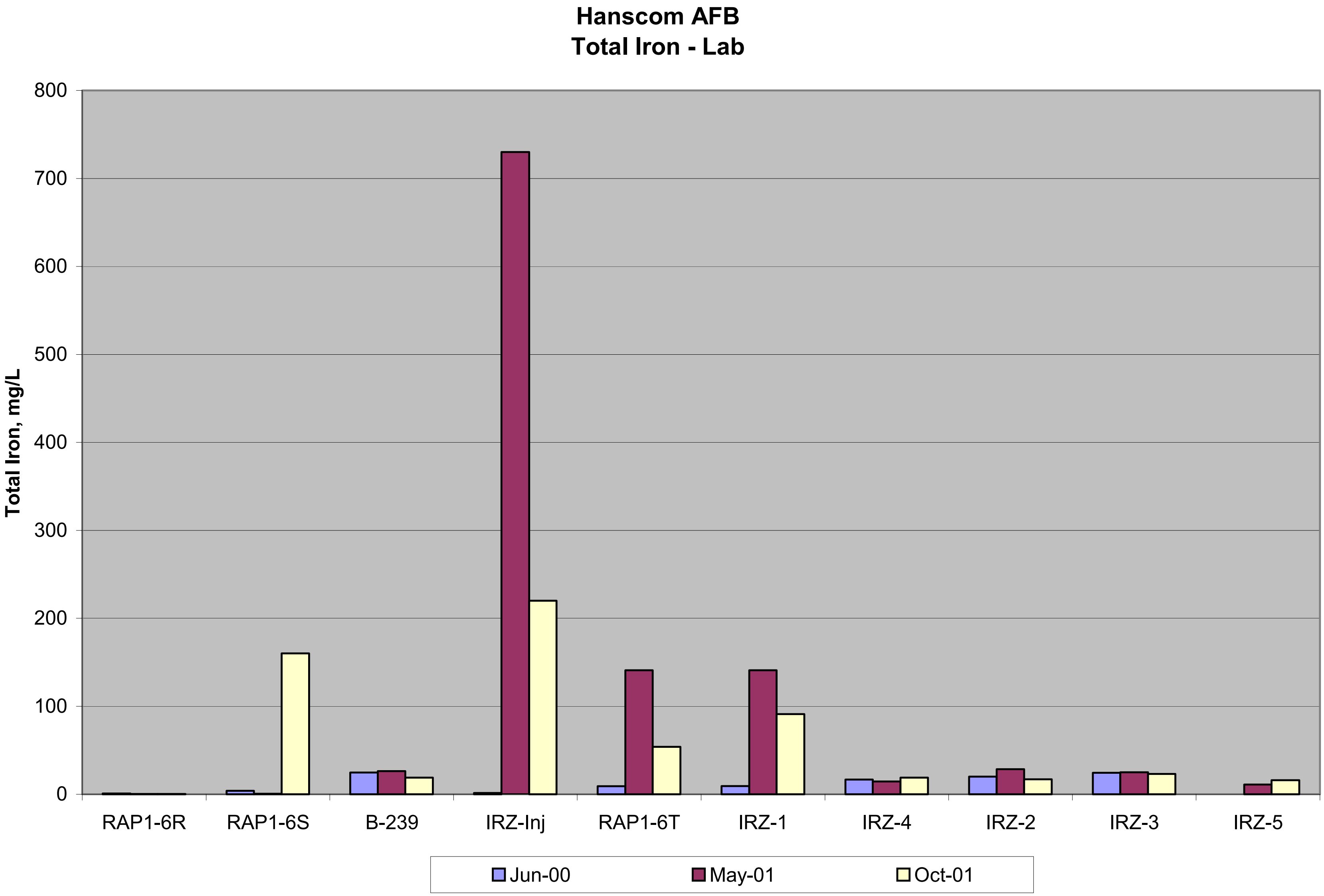


Figure 4-66. Total Iron –Lab

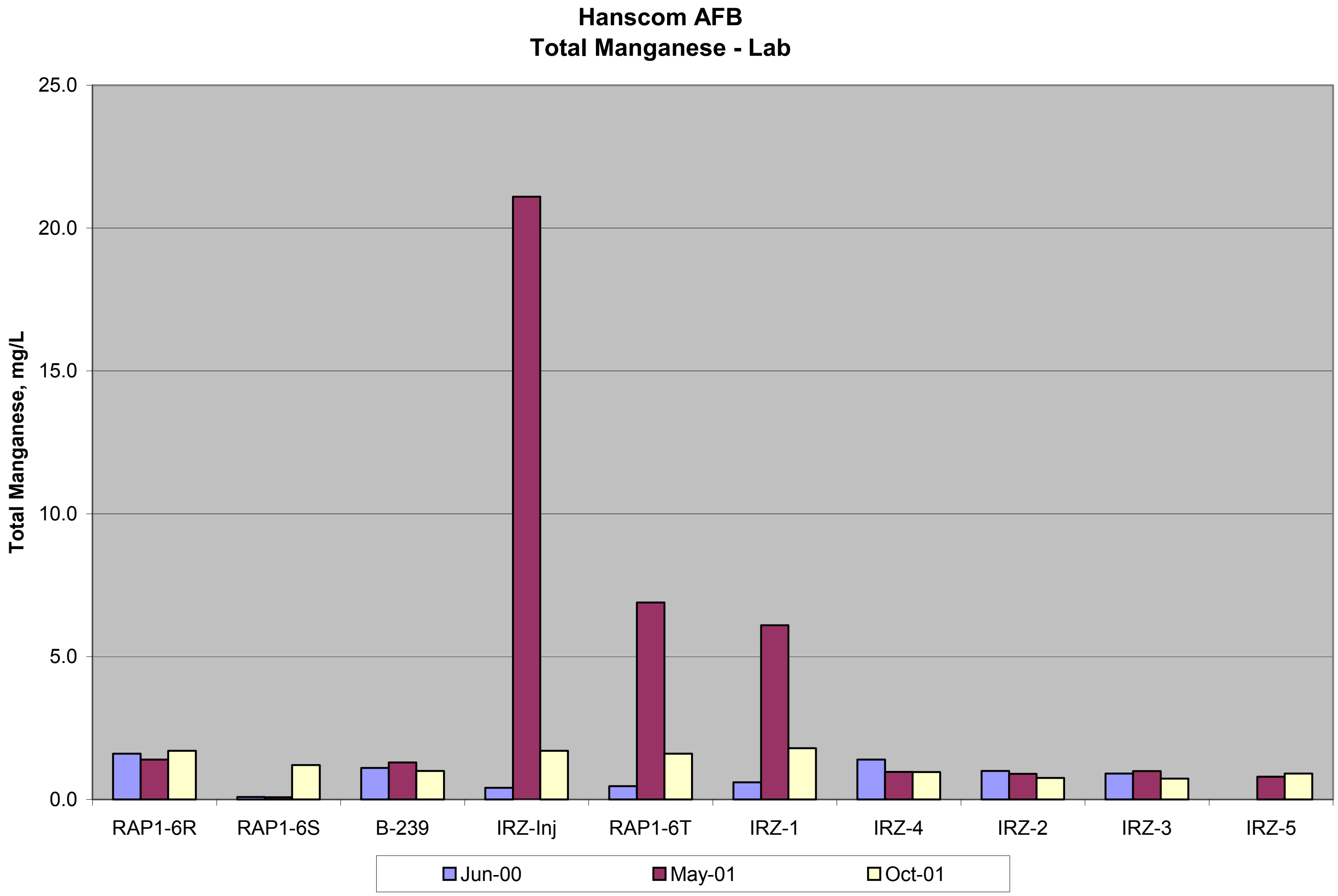


Figure 4-67. Total Manganese – Lab

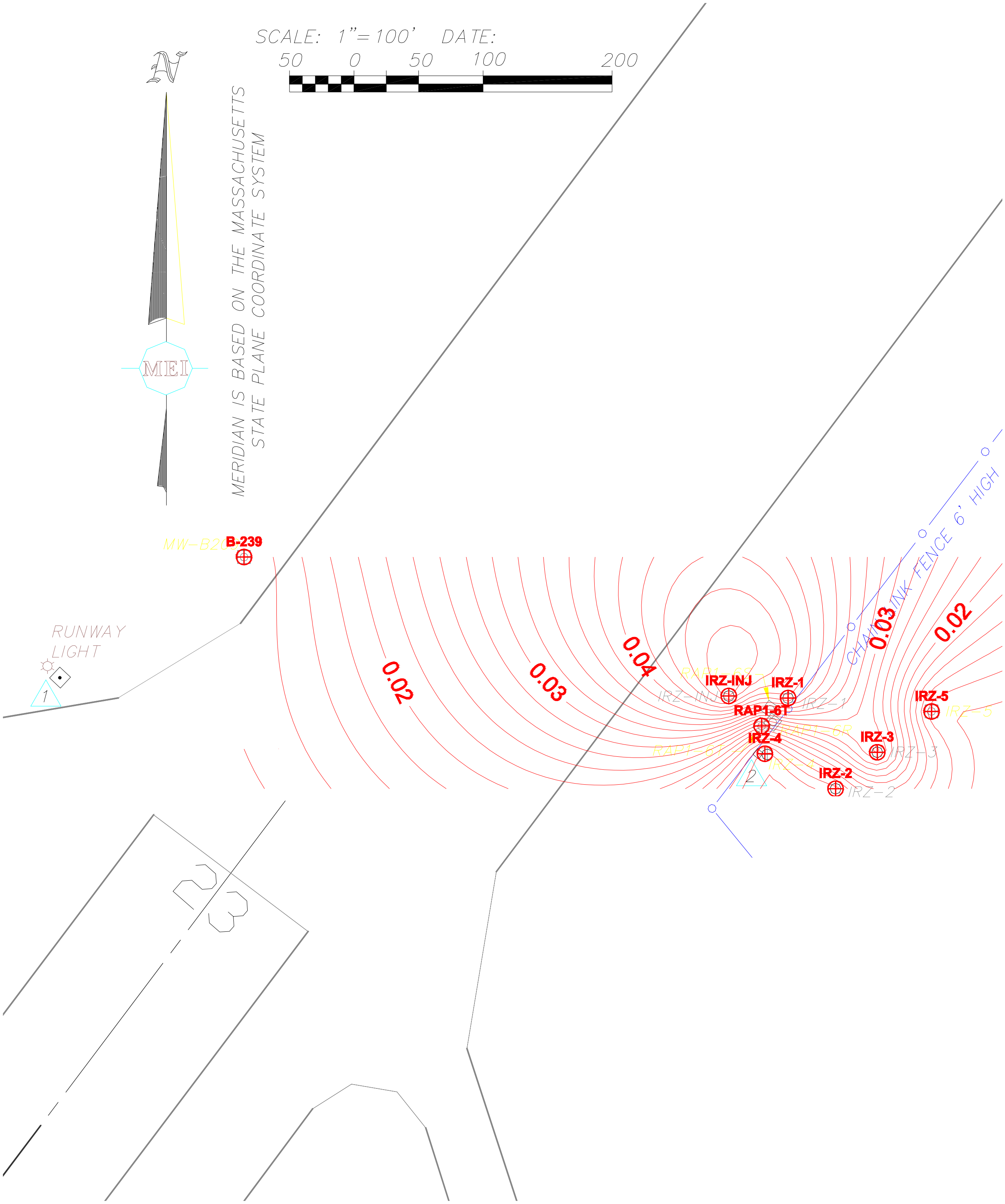


Figure 4-68. Total Arsenic in the Lower Aquifer from October 2002 Sampling Event

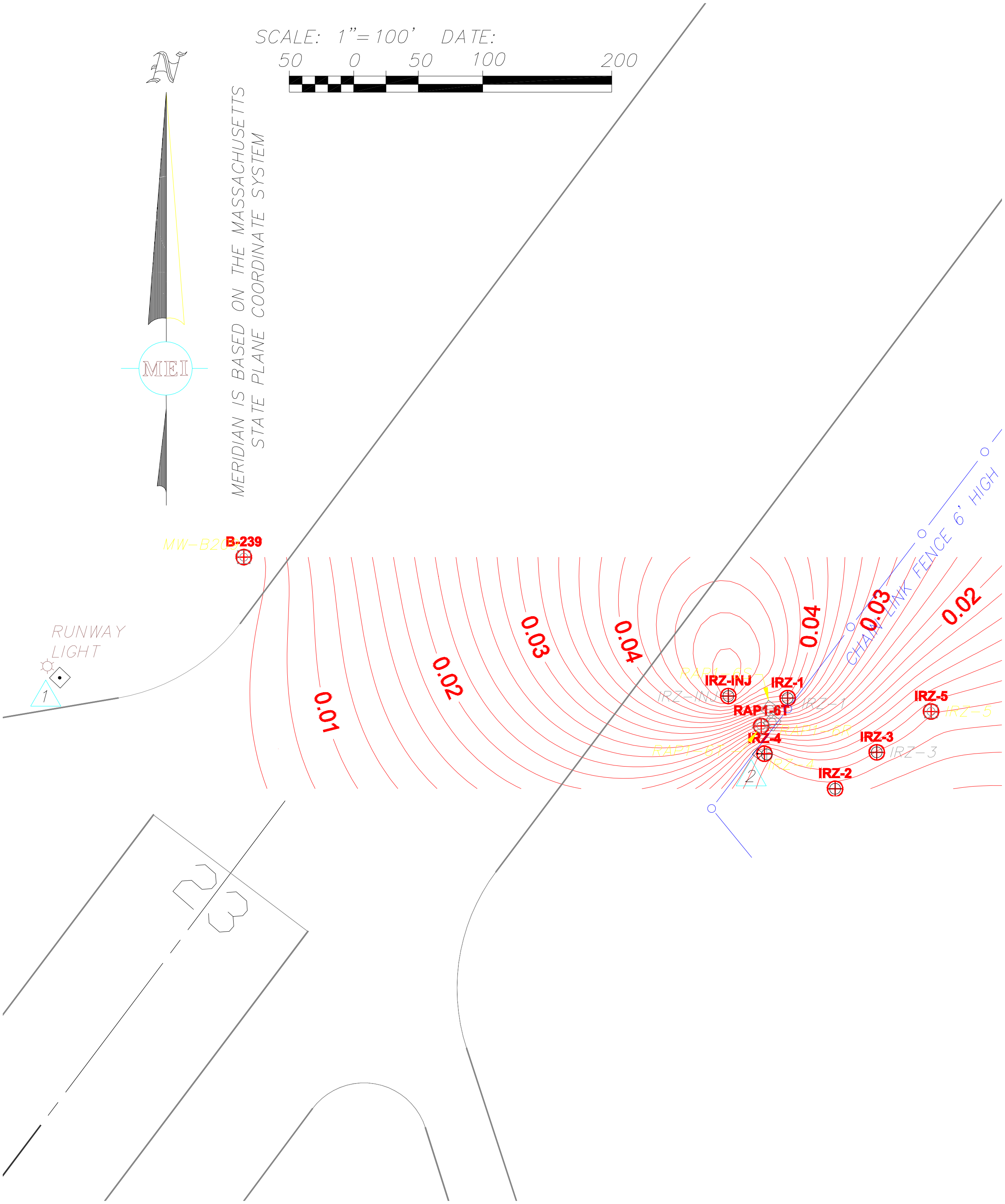


Figure 4-69. Dissolved Arsenic in the Lower Aquifer from October 2002 Sampling Event

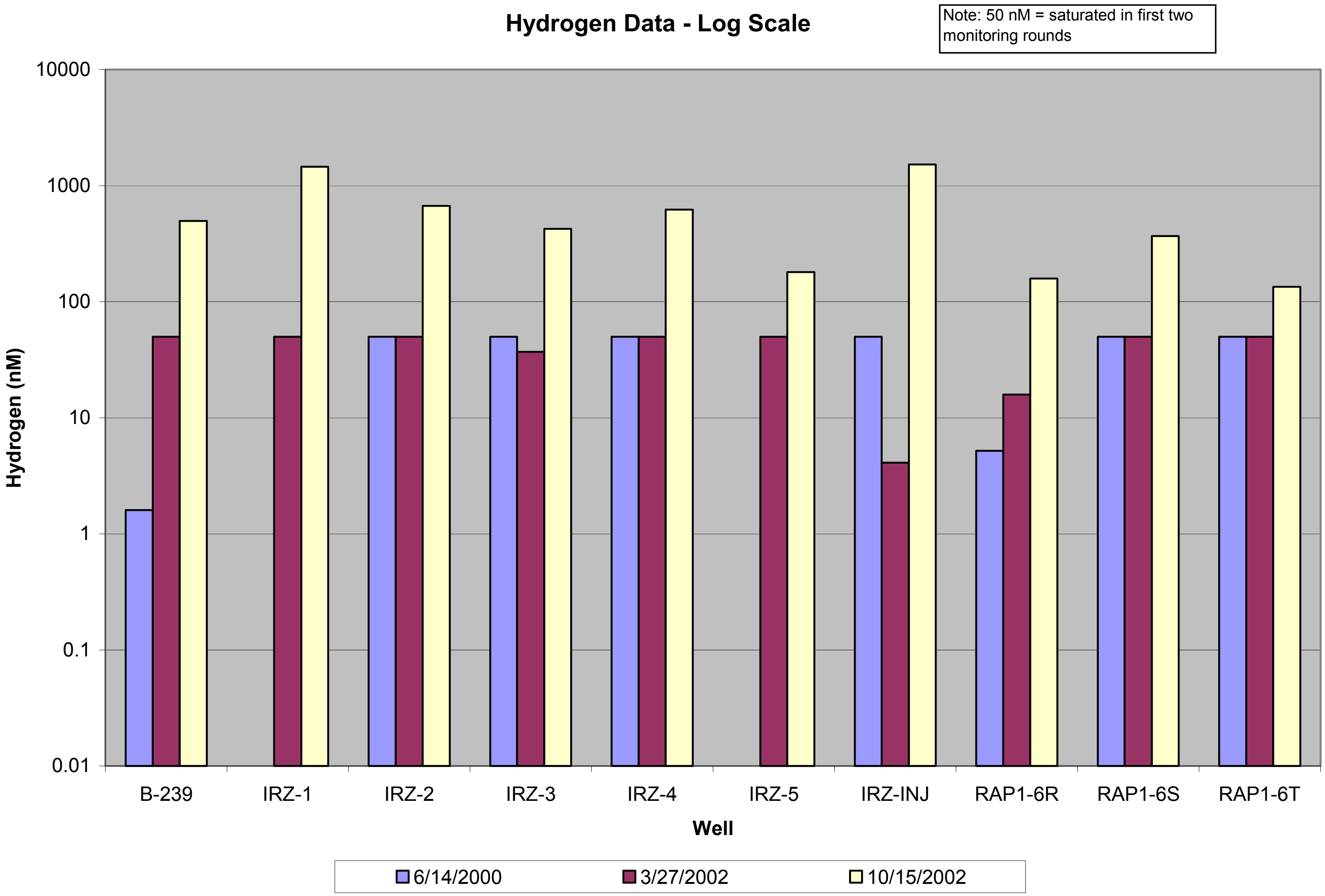


Figure 4-70. Hydrogen Data

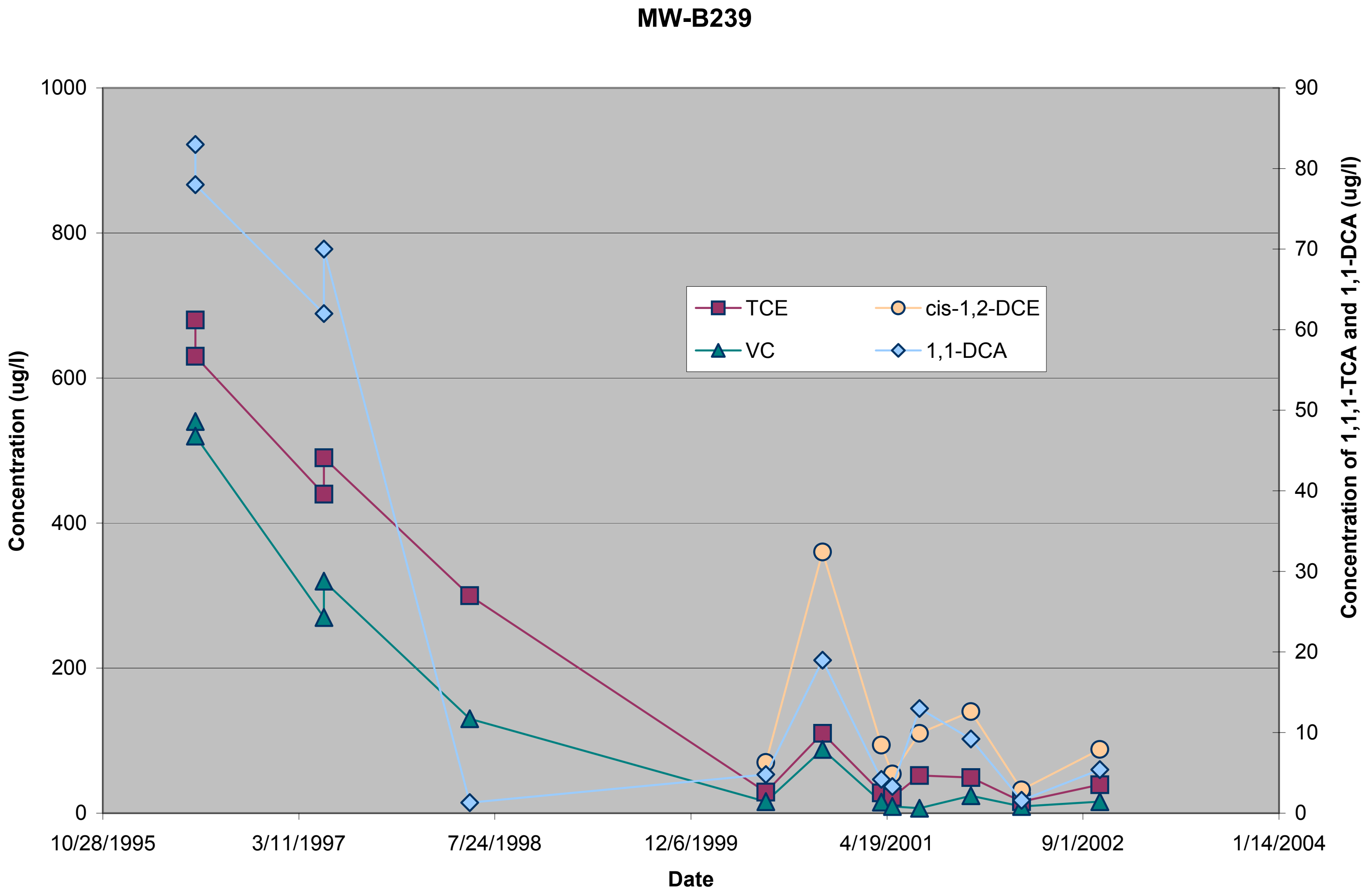


Figure 4-71. Concentration of CAHs at MW-B239

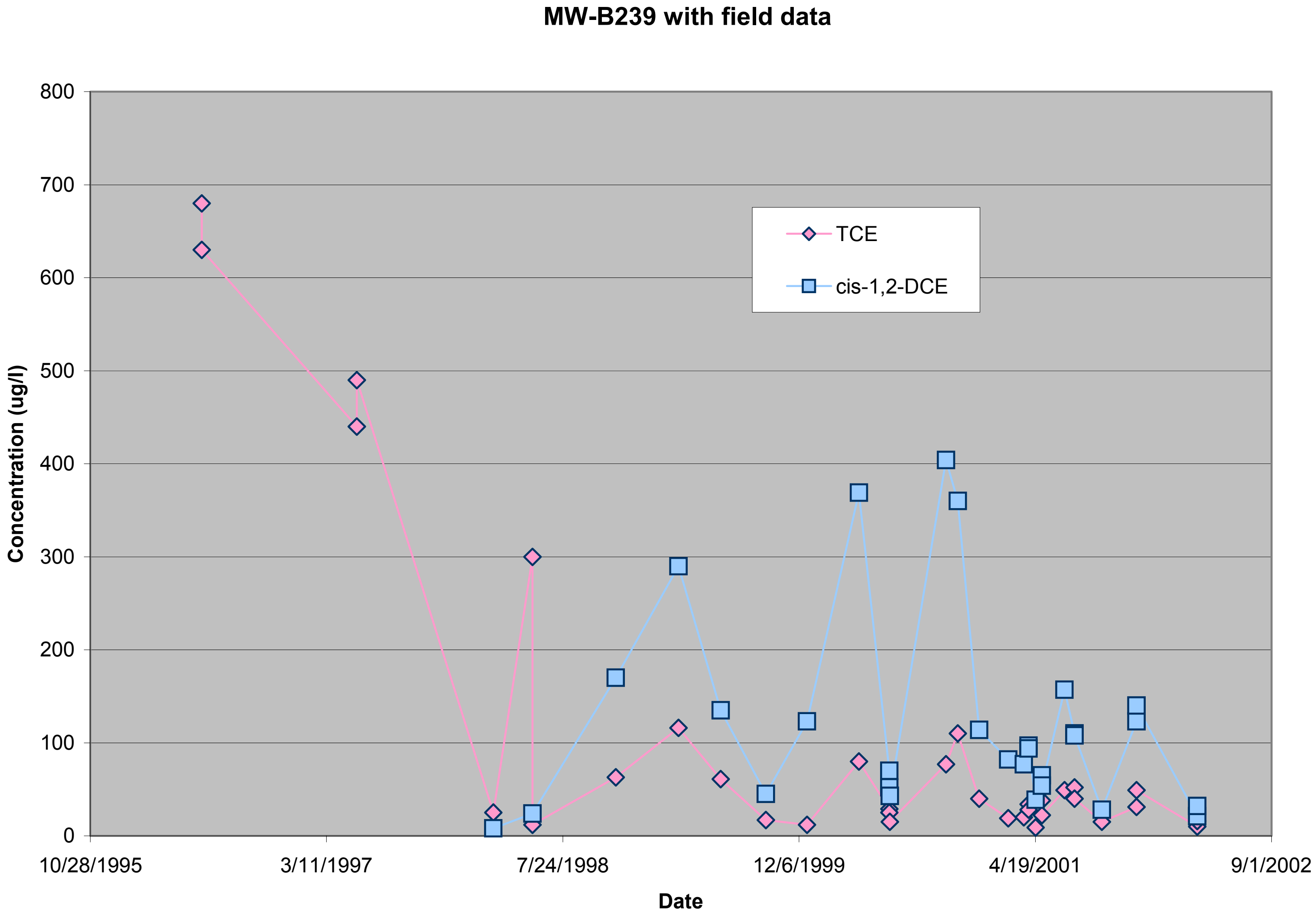


Figure 4-72. Concentration of CAHs at MW-B239, 10-28-1995 through 09-01-2002 with Field Data

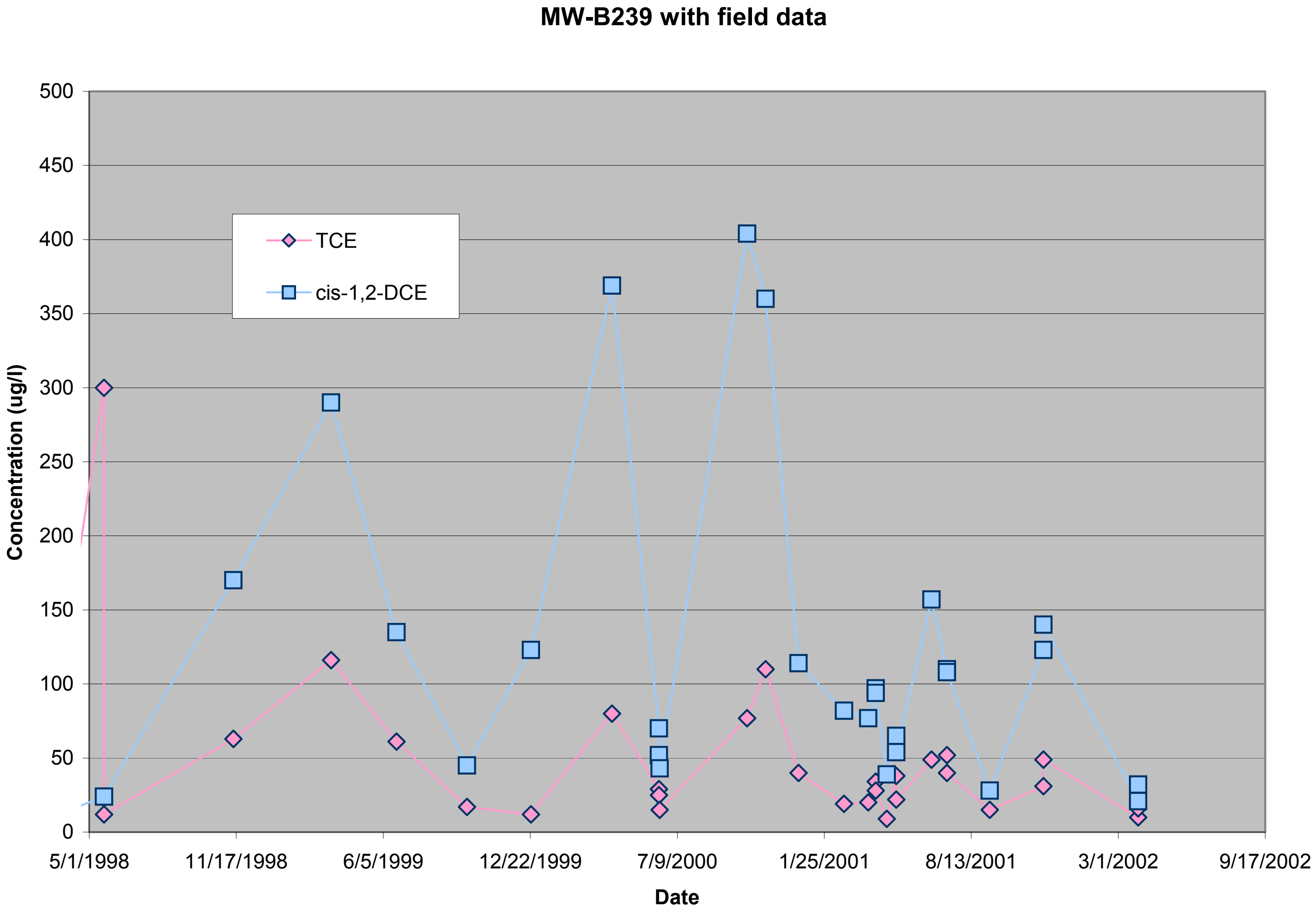


Figure 4-73. Concentration of CAHs at MW-B239, 05-01-1998 through 09-17-2002 with Field Data

Tables

Table 1-1. Summary of Physical Site Characteristics

SITE	DEPTH TO GW	HYDRAULIC CONDUCTIVITY	VELOCITY	GRADIENT	TREATMENT DEPTH
Hanscom	1.2 - 2.4 m BLS 4 – 8 ft BLS	~790 cm/d 26 ft/d	24 cm/d 0.8 ft/d	0.006 m/m or ft/ft	15 m BLS 50 ft BLS

Table 2-1. ERD Site Remediation Project Cost Elements

COST ELEMENT	COMMENTS
Costs incurred before treatment	
Engineering design	See text.
Work Plan preparation	Also include submittal and editing required for regulatory acceptance; permit preparation. Include costs for bid solicitation for subcontractors.
Mobilization and preparatory work	Includes mobilization for injection well installation and system construction. May also include installation of additional monitoring wells if the preexisting network is inadequate.
Well installation	Surface and subsurface structures at the facility may interfere with well design and placement. Proper planning and design can minimize these costs.
Treatment costs	
Field supervision	Oversight of subcontractors for drilling, laboratory analyses, etc.
Injection system	Manual batch loading of molasses into the injection well array can be performed using relatively low cost injection systems that may be truck or trailer mounted (see section 2.1 of this report and sections 4 and 6 of the protocol document, Suthersan 2002) . If a permanent injection set-up is required, additional capital costs will be incurred, including a system enclosure, permanent mixing tank/equipment, automated injection pumps and valving, and controls. Additional costs for this type of system may include below grade piping to transfer the solution from the enclosure to the wells and provision of utilities (water and electric). However, a portion of the costs associated with the more permanent installation will be off-set by the lower labor and field expense costs associated with the manual batch injections.
Substrate (food grade carbohydrate)	As mentioned in the text and in the protocol, these costs are relatively low on a per pound basis but can become substantial if a site requires high doses due to high flow or electron acceptor load. Feed rates are discussed in detail in protocol sections 4.3,4.5 and 5.3 (Suthersan 2002)
Labor, O&M	Automated loading of molasses into the injection well array will require more control equipment, but will reduce operations and maintenance costs.
Sampling and sample analysis	Labor required to collect groundwater samples from the treatment area. as well as costs for shipping, analysis and data interpretation should be included.
Utility costs	The main requirement should be a readily available source of potable water, preferably with a large flow rate near the site. Fuel for vehicles and electrical power or gasoline for pumps is also likely to be required but in small quantity.
Other costs	These include disposal of drill cuttings and purge water. During application of ERD, process waste is limited to disposal of contaminated groundwater generated during well purging.
Interim reporting	Technical performance and financial interim reports are normally required
After treatment costs	
Final reporting	Reports documenting system performance must be prepared for site closure.
Demobilization (equipment, material, and personnel.	Must include labor and subcontractor costs required to remove any equipment or surface facilities associated with the demonstrations. It must be assessed if injection and monitoring wells need to be removed/abandoned. Some site restoration can typically be anticipated.

Table 2-2. Summary of Reagent Cost Ranges for Selected Soluble Carbohydrates

Reagent	**Range of Costs (Per Pound of TOC)**	
	Low	**High**
Molasses (Food Grade)	$ 0.25	$ 0.60
Corn Syrup	$ 0.25	$ 0.44
Whey (Powder)	$ 1.17	$ 1.33
Sodium Lactate	$ 1.25	$ 1.46

Table 3-1. Performance Objectives

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance Objective Met?
Qualitative	1. Technology Evaluation - Gather information (for estimation of long-term treatment effectiveness, life span and costs) to use in a protocol for use of ERD technology for CAHs at DoD facilities	Collection of extensive performance data	Yes
Quantitative	2. Reduce Time to Remediate - Demonstrate the ability of ERD to remediate contaminants in the subsurface over a relatively short time period	1 to 5 years in typical full-scale applications	Time was limited but results support this metric
Quantitative	3. Contaminant Reduction (%) - Reduce total CAH concentrations from baseline levels of a) >200 ppb b) 50 to 200 ppb c) <50 ppb	a) 80% in 1 year b) 75% in 1 year c) 50% in 1 year	Yes for TCE; Qualified Yes for cis-DCE; in a limited area
Qualitative	4. Prevent "Stalling" - Demonstrate that degradation of CAHs by ERD does not stall at undesirable by-products (cis-DCE and/or VC)	Reduction of cis-DCE, VC after initial production, production of ethene	Yes in limited area
Type of Performance Objective	**Secondary Performance Criteria**	**Expected Performance (Metric)**	**Actual Performance Objective Met?**
Quantitative	5. Geochemistry Manipulation - Demonstrate the ability of ERD to enhance the anaerobic and reducing environment in groundwater where anaerobic conditions prevail	DO to <1 mg/L ORP <50 mV	Generally yes; anaerobic environment created within reactive zone
Quantitative	6. Contaminant Mobility - Evaluate the ability of ERD to desorb CAHs from aquifer materials	Presence of "spike" in concentration after initial injections	Yes in limited area
Quantitative	7. Contaminant Reduction (Rate) - Evaluate degradation rates before & after treatment	Calculate k	Yes

Type of Performance Objective	**Secondary Performance Criteria**	**Expected Performance (Metric)**	**Actual Performance Objective Met?**
Qualitative	8. System Performance Optimization - Determine optimal strengths and frequency of reagent delivery for the site	Injection Wells: pH > 4.5 DO < 1.0 mg/L -400 mV < ORP < -250 mV 500 mg/L < TOC < 5000 mg/L Sp. Cond. 10x increase Mon. Wells: pH > 5.0 DO < 1.0 mg/L ORP < -200 mV TOC > 50 mg/L Sp. Cond. 20-50% increase	Generally yes; continuously "tuned" system to metrics, determined required strength, frequency of injections (see Sections 4.3.2.1, 4.3.7.2)
Quantitative	9. Hazardous Materials	Potentially hazardous materials limited to soil cuttings from well drilling and purge water	Yes; no other haz. materials generated
Qualitative	10. Reliability	No significant reliability issues anticipated	Yes; reliability issues limited to well fouling, seal leakage
Qualitative	11. Ease of Use	Field implementation (substrate delivery) requires an environmental technician with 40 Hour HAZWOPER training, and office support from degreed scientists or engineers	Yes
Qualitative	12. Versatility	ERD can be used for other applications (e.g., metals, perchlorate) and under variable site conditions	N/A
Qualitative	13. Maintenance	Maintenance limited to occasional well development, normal equipment maintenance by technician	Yes
Qualitative	14. Scale-Up Constraints	Scale-up hasn't occurred at this site	N/A

Table 3-2. Suitability of Hanscom AFB Site Screening Characteristics for IRZ Implementation

Site Characteristic	Suitable for IRZ	Unsuitable for IRZ	Hanscom AFB
Aquifer hydraulic conductivity	> 1 ft/day	<0.01 ft/day	26 ft/day
Groundwater velocity	30 ft/year - 5 ft/day	< 30 ft/year, > 5 ft/day	0.8 ft/day
pH	6.0 – 8.0	< 5.0, > 9.0	5.7-7.1
Natural attenuation of CAHs	Slow, complete degradation, or stalled degradation	No degradation	Slow
DNAPL presence	None, or emulsified, sorbed, or residuals	IRZ not appropriate for targeting pooled DNAPL at this point in technology development	Although the demonstration site was believed to be well downgradient of the primary source area, and the initial dissolved phase concentrations did not indicate DNAPL according to the conventional definition (1-2% of solubility), later results suggested the presence of a source in the demonstration area.
Sulfate	< 700 ppm		39 ppm, max
Redox	Aerobic or borderline	Anaerobic with sufficient TOC	Borderline: DO of 0.5 to 1 mg/l, ORP of –60 to 200 mv
Depth of Target Zone		>50 feet can become expensive	50 feet
CAH concentration	Non-toxic	Toxic	Non-Toxic

Table 3-3. Pre-demonstration Project Concentrations of Volatile Organic Compounds in Wells RAP1-6R and RAP1-6T

Concentration Data/Bedrock Aquifer

RAP1-6R	Feb-86	Mar-86	Oct-87	Sep-88	Nov-90	Feb-91	Aug-91	Jul-94	Nov-94	Jun-96	May-97	May-98
PCE	11	NS	1	1	5.4	9.6	14	1	1	1	1	1
TCE	820	NS	730	1400	570	670	760	1100	1400	1800	1600	1800
1,1,1-TCA	70	NS	36	1	22	50	32	1	1	1	1	1
1,2-DCA	8.5	NS	1	1	14	36	10	1	1	1	1	1
1,2-DCE	2600	NS	2900	5000	2600	680	1800	3500	3700	4932	4800	4800
1,1-DCE	48	NS	42	60	37	64	95	69	110	130	130	1
1,1-DCA	60	NS	77	140	84	140	130	130	190	240	230	1
VC	67	NS	220	340	170	460	300	600	710	990	850	1300
Total VOCs	**3685**		**4007**	**6943**	**3502**	**2110**	**3141**	**5402**	**6113**	**8095**	**7613**	**7905**

Concentration Data/Lower Aquifer

RAP1-6T	Feb-86	Mar-86	Oct-87	Sep-88	Nov-90	Feb-91	Sep-91	Jul-94	Nov-94	Jun-96	May-97	May-98
PCE	6.6	7.1	1	1	3.8	1	13	1	1	1	1	1
TCE	650	550	340	430	450	600	1400	1800	2500	2200	2000	1600
1,1,1-TCA	300	290	130	120	130	160	62	1	1	30	1	1
1,2-DCA	17	18	1	1	9.7	58	11	1	1	1	1	1
1,2-DCE	5000	6000	3200	3000	2700	1000	2900	4200	5000	6200	6600	3800
1,1-DCE	96	84	42	1	61	68	140	1	1	210	220	1
1,1-DCA	190	160	110	98	120	130	220	1	270	350	350	1
VC	780	760	510	560	570	660	1200	950	1200	1600	1600	1
Total VOCs	**7040**	**7869**	**4334**	**4211**	**4045**	**2677**	**5946**	**6955**	**8974**	**10592**	**10773**	**5406**

PCE	tetrachloroethene
TCE	trichloroethene
1,1,1-TCA	1,1,1-trichloroethane
1,2-DCA	1,2-dichloroethane
1,2-DCE	1,2-dichloroethene
1,1-DCE	1,1-dichloroethene
1,1-DCA	1,1-dichloroethane
VC	vinyl chloride
NS	not sampled

Notes: All sample results are reported in micrograms per liter (ug/L)
Sample results shown as 1, represent concentrations less than the detection limit of 1 ug/L.

Table 3-4. Soil Analysis Summary

Analysis	**IRZ-Inj (44-46)**	**HAN-SS-IRZ-1 (44-45)**	**IRZ-1 Dup (44-45)**	**IRZ-2 (39-41)**	**IRZ-3 (44-46)**	**IRZ-3 Dup (44-46)**	**IRZ-4 (44-46)**	**TB-01**
Volatile Organic Compounds (ug/kg)								
1,2-Dichloroethene (total)	19	28	NA	18	18	22	8.5	1 U
Vinyl chloride	10 U	2.4 J	NA	1.1 J	0.83 J	2.4 J	11 U	1 U
Acetone	12 J	21 J	NA	27 U	16 J	19 J	18 J	10 U
Carbon disulfide	5.1 U	5.6 U	NA	5.5 U	1.4 J	1.1 J	5.5 U	1 U
1,1-Dichloroethane	2.6 J	2.2 J	NA	2.2 J	4.5 J	5.3 J	3.4 J	1 U
cis-1,2-Dichloroethene	19	28	NA	18	18	22	8.5	1 U
Trichloroethene	6.9	6.7	NA	5 J	6.8	6.2	3.3 J	1 U
Total Organic Carbon (mg/kg)	2000 U	1900 B	1570 B	2000 U	770 B	NA	2000 U	NA
Grain Size Description	Gray silty gravel with sand	Gray silty sand with gravel	Gray poorly graded gravel with silt and sand	Gray silty sand with gravel	Gray silty sand with gravel	---	Gray silty sand with gravel	---

Notes:

Only detected compounds listed

VOCs analyzed by method SW846 8260B, by Severn Trent Laboratories, Inc. of Tampa, FL

TOC analyzed by method SW846 9060, by Severn Trent Laboratories, Inc. of Tampa FL

Grain size analysis performed by Engineering Consulting Services, Ltd. Of Research Triangle Park, NC

J = Estimated result

B = Estimated result

NA = Not analyzed

Table 3-5. Summary of Initial, Background Biogeochemical Data (min/max)

	DO	ORP	PH	NITRATE	SULFATE	SULFIDE	CO_2	METHANE
SITE	(mg/l)	(mv)	(s.u.)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(μg/l)
Hanscom	0.35	-57.5	5.73	ND	21.5	ND	9.4	15.0
	1.48	200	7.10		38.9	0.1	86.2	138.8

Table 3-6. History Log of Demonstration

Week	Dates (from - to)		Event
1	10/9/2000	10/15/2000	Initial injection 10-11-00
2	10/16/2000	10/22/2000	Process monitoring #1 w/TOC 10-18-00
3	10/23/2000	10/29/2000	Process monitoring #2 w/TOC 10-25-00
4	10/30/2000	11/5/2000	Process monitoring #3 w/TOC 11-1-00
5	11/6/2000	11/12/2000	Abbreviated monitoring #1 w/TOC, sulfide, Br, CAHs 11-6/7-00, injection #2 11-8-00
6	11/13/2000	11/19/2000	
7	11/20/2000	11/26/2000	Injection #3 11-21-01
8	11/27/2000	12/3/2000	Process monitoring #4 w/TOC 11-30-00
9	12/4/2000	12/10/2000	
10	12/11/2000	12/17/2000	
11	12/18/2000	12/24/2000	Process monitoring #5 w/TOC, injection #4 12-21-00
12	12/25/2000	12/31/2000	
13	1/1/2001	1/7/2001	Process monitoring #6 w/TOC Br- 1-4-01
14	1/8/2001	1/14/2001	Process monitoring #7 w/TOC Br- 1-11-01
15	1/15/2001	1/21/2001	Injection #5 1-15-01
16	1/22/2001	1/28/2001	
17	1/29/2001	2/4/2001	Process monitoring #8 w/TOC, Br-, injection #6 1-31-01
18	2/5/2001	2/11/2001	
19	2/12/2001	2/18/2001	
20	2/19/2001	2/25/2001	Injection #7 with clean water push 2-20-01
21	2/26/2001	3/4/2001	
22	3/5/2001	3/11/2001	
23	3/12/2001	3/18/2001	
24	3/19/2001	3/25/2001	Process monitoring #9, injection #8 with clean water push 3-19-01
25	3/26/2001	4/1/2001	Injection #9 with clean water push 3-26-01 with sampling.
26	4/2/2001	4/8/2001	
27	4/9/2001	4/15/2001	Injection #10 with clean water push, abbreviated monitoring #2 4-9-01
28	4/16/2001	4/22/2001	
29	4/23/2001	4/29/2001	Injection #11 with clean water push 4-23-01
30	4/30/2001	5/6/2001	5/3-5/8 midpoint full monitoring round and installation of IRZ-5
31	5/7/2001	5/13/2001	IRZ-5 developed 5-8-01, injection #12 with clean water push 5-9-01
32	5/14/2001	5/20/2001	
33	5/21/2001	5/27/2001	Injection #13 with clean water push 5-22-01.
34	5/28/2001	6/3/2001	
35	6/4/2001	6/10/2001	Injection #14 with clean water push 6-4-01.
36	6/11/2001	6/17/2001	
37	6/18/2001	6/24/2001	Injection #15 with clean water push 6-18-01 along with water surface measurements.
38	6/25/2001	7/1/2001	
39	7/2/2001	7/8/2001	
40	7/9/2001	7/15/2001	Injection #16 with water push 7-12-01 with abbreviated monitoring #3

Week	Dates (from - to)		Event
41	7/16/2001	7/22/2001	
42	7/23/2001	7/29/2001	Injection #17 with water push 7-25-01.
43	7/30/2001	8/5/2001	
44	8/6/2001	8/12/2001	Injection #18 with water push 8-7-01.
45	8/13/2001	8/19/2001	
46	8/20/2001	8/26/2001	Injection #19 with water push 8-22-01.
47	8/27/2001	9/2/2001	
48	9/3/2001	9/9/2001	Double injection #1 (Injection #20) with standard water push 9-7-01.
49	9/10/2001	9/16/2001	
50	9/17/2001	9/23/2001	Double injection #2 (Injection #21) with standard water push 9-19-01.
51	9/24/2001	9/30/2001	
52	10/1/2001	10/7/2001	Double injection #3 (Injection #22) with standard water push 10-3-01.
53	10/8/2001	10/14/2001	Process monitoring #10 10/12/01
54	10/15/2001	10/21/2001	Water push 10-16-01.
55	10/22/2001	10/28/2001	
56	10/29/2001	11/4/2001	Double injection #4 (Injection #23) with standard water push 10-30-01.
57	11/5/2001	11/11/2001	
58	11/12/2001	11/18/2001	11-13-01 Injection #24 (single)
59	11/19/2001	11/25/2001	Abbreviated monitoring #4 11-19-01
60	11/26/2001	12/2/2001	Double injection #5 (Injection #25) with double water push 11-26-01.
61	12/3/2001	12/9/2001	
62	12/10/2001	12/16/2001	Double injection #6 (injection #26) with double water push 12-11-01.
63	12/17/2001	12/23/2001	
64	12/24/2001	12/30/2001	Double injection #7 (injection #27) with a little more than a single push 12-26-01.
65	12/31/2001	1/6/2002	
66	1/7/2002	1/13/2002	Double injection #8 (injection #28) with single push 1-8 and 1-9-02.
67	1/14/2002	1/20/2002	
68	1/21/2002	1/27/2002	Process monitoring #11, 1-22-02. Double injection #9 (injection #29) with single push 1-23-02.
69	1/28/2002	2/3/2002	
70	2/4/2002	2/10/2002	Single injection #25 (injection #30) with single push 2-5-02.
71	2/11/2002	2/17/2002	
72	2/18/2002	2/24/2002	Double injection #10 (injection #31) with half push 2-19-02. TOC/DOC/Br sampling 2-22-02.
73	2/25/2002	3/3/2002	
74	3/4/2002	3/10/2002	Water push only (#2) 3-5-02. Limited process monitoring (#12).
75	3/11/2002	3/17/2002	pH on IRZ-INJ and single molasses injection/single push #26 (injection #32) 3-12-02.
76	3/18/2002	3/24/2002	Half injection with water push #1 (injection #33) 3-19-02.
77	3/25/2002	3/31/2002	3-27 and 3-28-02: abbreviated monitoring #5 with gas sampling
78	4/1/2002	4/7/2002	Single injection #27 (Injection #34) with single push 4-2-02
79	4/8/2002	4/14/2002	
80	4/15/2002	4/21/2002	Double injection #11 (Injection #35) with single push and pH on IRZ-INJ 4-16-02

Week	Dates (from - to)		Event
81	4/22/2002	4/28/2002	
82	4/29/2002	5/5/2002	Single injection #28 (Injection #36) with single push and pH on IRZ-INJ 4-30-02.
83	5/6/2002	5/12/2002	
84	5/13/2002	5/19/2002	Water level measurements on 5-14-02.
85	5/20/2002	5/26/2002	Double injection #12 (Injection #37) with water push and pH on IRZ-INJ 5-20-02.
86	5/27/2002	6/2/2002	
87	6/3/2002	6/9/2002	Single injection #29 (Injection #38) with water push and limited process monitoring #13 6-6-02.
88	6/10/2002	6/16/2002	
89	6/17/2002	6/23/2002	Single injection #30 (Injection #39) with water push and pH on IRZ-INJ 6-18-02.
90	6/24/2002	6/30/2002	
91	7/1/2002	7/7/2002	Single injection #31 (Injection #40) with water push and pH on IRZ-INJ 7-2-02.
92	7/8/2002	7/14/2002	
93	7/15/2002	7/21/2002	Single injection #32 (Injection #41) with water push and pH on IRZ-INJ 7-16-02.
94	7/22/2002	7/28/2002	
95	7/29/2002	8/4/2002	Lawnmower damage discovered 7-29-02. 7-30-02 single injection #33 (inj. #42), with pH. Single push on 8-1-02
96	8/5/2002	8/11/2002	
97	8/12/2002	8/18/2002	8-12-02 200 gallon water push.
98	8/19/2002	8/25/2002	
99	8/26/2002	9/1/2002	Double injection #13 (Injection #43) with water push and pH in IRZ-INJ 8-28-02.
100	9/2/2002	9/8/2002	
101	9/9/2002	9/15/2002	
102	9/16/2002	9/22/2002	Water level and TOC/Br samples 9-16-02. Double injection #14 (Inj. #44) w/water push and IRZ-INJ pH 9-18-02.
103	9/23/2002	9/29/2002	Double injection #15 (Injection #45) with water push and pH in IRZ-INJ 9-24-02.
104	9/30/2002	10/6/2002	Double injection #16 (Injection #46) with water push 10-2-02, pH in IRZ-INJ and water levels on 10-1-02.
105	10/7/2002	10/13/2002	Single injection #33 (Injection #47) with water push 10-9-02, pH in IRZ-INJ and water levels.
106	10/14/2002	10/20/2002	10-14 through 10-16-02 Final sampling round.
107	10/21/2002	10/27/2002	
108	10/28/2002	11/3/2002	10-29-02 Remeasurement of final round field parameters.

End of Table 3-6. History Log of Demonstration

Table 3-7. Parameters Included in Full and Abbreviated Groundwater Monitoring Events

Parameter	Analytical Method	Concentration Units Reported In	Volume, Container, Preservative & Storage Requirements	Hold Time	Parameter Included also In Abbreviated Monitoring Events?	Location of test/ Firm
Temperature	ARCADIS SOP D1 (based on EPA 170.1)	Degrees C	NA	Analyze immediately	Y	ARCADIS in the field
ORP	See appendix 'field procedures' & 'instrument calibration procedures'	mV	NA	Analyze immediately	Y	ARCADIS in the field
Dissolved Oxygen	ARCADIS SOP D5 (Based on EPA 360.1)	mg/L	NA	Analyze immediately	Y	ARCADIS in the field
PH	ARCADIS SOP D2 (based on EPA 150.1)	S.U.	NA	Analyze immediately	Y	ARCADIS in the field
Specific Conductance	ARCADIS SOP D3 based on standard methods for examination of water & wastewater, 15th edition method 205 & USEDA method 120.1	microsiemens/cm	NA	Analyze immediately	Y	ARCADIS in the field
Alkalinity	310.1	mg/L	250 mL Glass or plastic Cool to 4 °C	14 days	N	STL

Parameter	**Analytical Method**	**Concentration Units Reported In**	**Volume, Container, Preservative & Storage Requirements**	**Hold Time**	**Parameter Included also In Abbreviated Monitoring Events?**	**Location of test/ Firm**
Nitrate	300.0A	mg/L	250 mL Glass or plastic Cool to 4 °C	48 hours	N	STL
Nitrite	300.0A	mg/L	250 mL Glass or plastic Cool to 4 °C	48 hours	N	STL
Sulfate	300.0A	mg/L	100 mL Glass or plastic Cool to 4 °C	28 days	N	STL
Chloride	300.0A	mg/L	250 mL Glass or plastic	28 days	N	STL
Methane, Ethane, Ethene	Modified RSK-175, WA 1.02	ug/l	Glass VOA vials	7 days	N	Vaportech
Carbon Dioxide	WA 2.01 modified	mg/l	Glass VOA vials	7 days	N	Vaportech
Chemical Oxygen Demand	410.4 or 410.1	mg/L	250 mL Glass or Plastic Cool to 4 °C H_2SO_4 to pH<2	28 days	N	STL
Biochemical Oxygen Demand	405.1	mg/L	100 mL Glass or plastic Cool to 4 °C	48 hours	N	STL

Parameter	Analytical Method	Concentration Units Reported In	Volume, Container, Preservative & Storage Requirements	Hold Time	Parameter Included also In Abbreviated Monitoring Events?	Location of test/ Firm
Total Organic Carbon (TOC)	415.1	mg/L	100 mL Glass or Plastic Cool to 4 °C H_2SO_4 to pH<2	28 days	Y	STL
Dissolved Total Organic Carbon	415.1	mg/L	100 mL Glass or Plastic Cool to 4 °C H_2SO_4 to pH<2	28 days	Y	STL
Ammonia	350.1	mg/L	500 mL Glass or Plastic Cool to 4 °C H_2SO_4 to pH<2	28 days	N	STL
Sulfide	Color Chart/ Effervescence of H_2S (Hach Kit 25378-00)	mg/L	500 mL Glass or Plastic Cool to 4 °C H_2SO_4 to pH<2	7 days	Y	ARCADIS in the field
Total Iron	6010B and CHEMetrics kit in field	ug/L	1 L Glass or plastic HNO_3 to pH<2	6 months	N	STL, Also in field by ARCADIS
Total Manganese	6010B and CHEMetrics kit in field based on APHA 314C and CHEMetrics kit in field	ug/L	1 L Glass or plastic HNO_3 to pH<2	6 months	N	STL, Also in field by ARCADIS

Parameter	**Analytical Method**	**Concentration Units Reported In**	**Volume, Container, Preservative & Storage Requirements**	**Hold Time**	**Parameter Included also In Abbreviated Monitoring Events?**	**Location of test/ Firm**
Dissolved Iron	6010B and CHEMetrics kit in field	ug/L	1 L Glass or plastic HNO_3 to pH<2	6 months	N	STL, Also in field by ARCADIS
Dissolved Manganese	6010B and CHEMetrics kit in field (APHA 314C)	ug/L	1 L Glass or plastic HNO_3 to pH<2	6 months	N	STL, Also in field by ARCADIS
CAHs	8260	ug/L	VOA vials, no headspace HCl to pH<2; Cool to 4 °C	14 days	Y	STL
Hydrogen	RSK-196	nM/L	Special; see text Re: dissolved gas sampling	28 days	N	Vaportech
Explosives (Badger AAP only)	8330	ug/L	Glass or teflon store @ 4 °C	14 days/extract analyzed within 40 days	Y	STL
Bromide	300.0	mg/l	250 ml plastic or glass unpreserved	28 days	Y	STL

Table 3-8. Parameters Included in Soil Monitoring Events

Parameter	Analytical Method	Concentration Units Reported In	Container & Preservative Requirements	Hold Time	Parameter Included also In Abbreviated Monitoring Events?	Location of test
Total Organic Carbon (TOC)	9060	mg/kg	None specified	28 days	Y	STL
CAHs	8260	ug/kg	4 oz. Glass with teflon lined septa; store @ 4 °C	14 days	Y	STL
Explosives	8330	ug/kg	250 mL glass w/teflon lined septa; cool to 4 °C	14 days/extract in analyzed within 40 days	Y	STL
Grain Size	ASTM D-422	% passing	500 mL wide mouth glass or plastic (purchased by field crew)	None	Y	ECS

Table 4-1. Performance Criteria

Performance Criteria	Description	Primary or Secondary
Technology Evaluation	Gather information to use in a protocol for use of IRZ technology for CAHs at DoD facilities	Primary
Reduce Time to Remediate	Demonstrate the ability of ERD to remediate contaminants in the subsurface over a relatively short time period	Primary
Contaminant Reduction	Reduction of baseline levels of CAHs, primarily TCE, cis-1,2-DCE, and VC at Hanscom AFB	Primary
	Enhancement of CAH degradation rates	Secondary
Prevent "Stalling"	Demonstrate that degradation of CAHs by ERD does not stall at undesirable by-products (cis-DCE and/or VC)	Primary
Geochemistry Manipulation	Demonstrate the ability of ERD to enhance the anaerobic and reducing environment where anaerobic conditions prevail	Secondary
Contaminant Mobility	a. Evaluate the ability of ERD to desorb CAHs from aquifer materials	Secondary
	b. Evaluate the propensity of ERD to mobilize metals	Secondary
System Performance Optimization	Determine optimal strengths and frequency of reagent delivery for the site	Secondary
Hazardous Materials	Identify any hazardous materials introduced or generated by ERD technology	Secondary
Reliability	Identify potential problems that may cause system shutdowns	Secondary
Ease of Use	Describe the number of people, skill level(s) and safety training required to perform injections and monitoring	Secondary
Versatility	Describe whether ERD can be used for other applications and under other site conditions	Secondary
Maintenance	Identify operations and maintenance requirements and level of training required to implement O&M	Secondary
Scale-Up Constraints	Identify engineering constraints associated with scaling up an ERD system	Secondary

Table 4-2. Expected Performance and Performance Confirmation Methods

Performance Criteria	Expected Performance Metric (Pre-Demonstration)	Performance Confirmation Method	Actual (Post-Demonstration)
PRIMARY CRITERIA (Performance Objectives) (Qualitative)			
Technology Evaluation	Collection of extensive performance data	Body of data from 11 monitoring wells conforms to demonstration plan	Performance data collection plan was met with few exceptions
Prevent "Stalling"	Reduction of cis-DCE, VC after initial production, production of ethene	CAH and ethene data from wells IRZ-1 and RAP1-6T in the reactive zone	Ethene concentrations rose to more than 20 times pre-test value at IRZ-1, 5 times pre-test value at RAP1-6T
PRIMARY CRITERIA (Performance Objectives) (Quantitative)			
Reduce Time to Remediate	1 to 5 years in typical full-scale applications	Evidence of contaminant reductions (% and rates) and ethene production	In the 2-year pilot, observed significant contaminant reductions and ethene production (see Sections 4.3.3.5 and 4.3.7.1), suggesting that remediation time of 5 years or less is realistic for a full-scale system
Contaminant Reduction (%)	Total CAH concentrations reduced by at least 80% in 1 year	CAH data from IRZ-1 and RAP1-6T, from baseline sampling through October 2002	IRZ-1: TCE reduced >95% in 5 months. Cis-DCE reductions >85% in 17 months. VC reductions 41% in 17 months. RAP1-6T: TCE reduced >80% in 1 year, cis-DCE and VC increased due to inadequate substrate delivery (see Section 4.3.7.1)

Performance Criteria	Expected Performance Metric (Pre-Demonstration)	Performance Confirmation Method	Actual (Post-Demonstration)
SECONDARY CRITERIA (Performance Objectives) (Qualitative)			
System Performance Optimization	Injection Wells: pH > 4.5 DO < 1.0 mg/L -400 mV < ORP < -250 mV 500 mg/L < TOC < 5000 mg/L Sp. Cond. 10x increase Mon. Wells: pH > 5.0 DO < 1.0 mg/L ORP < -200 mV TOC > 50 mg/L Sp. Cond. 20-50% increase	Performance monitoring data evaluated before each injection event to determine optimal strengths and frequency of reagent delivery for the site	An anaerobic environment was created within the reactive zone with few exceptions to performance criteria (see Section 4.3.7.2). Strength and frequency of injection discussed in Sections 4.3.2.1 and 4.3.7.2
Reliability	No significant reliability issues anticipated	Field records	Met performance metric; minor corrective actions needed for well fouling and seal leakage (Section 3.5.1)
Ease of Use	Field implementation (substrate delivery) requires an environmental technician with 40-hr HAZWOPER training, and office support from degreed scientists or engineers	Experience from demonstration operation and other site applications	Met performance metric for substrate delivery. Geologist required for permanent well installations.
Versatility	ERD can be used for other applications (e.g., metals, perchlorate) and under variable site conditions	Experience from other site applications	Versatility discussed in Sections 1.1, 2.1.1

Performance Criteria	**Expected Performance Metric (Pre-Demonstration)**	**Performance Confirmation Method**	**Actual (Post-Demonstration)**
Maintenance	Maintenance limited to occasional well development, normal equipment maintenance by technician	Field records	Met performance metric; maintenance issues discussed in Section 3.5.1
Scale-Up Constraints	Primary scale-up issues anticipated to be efficacy of manual batch injection mode and area of influence determination	Experience from demonstration operation and other site applications	Scale-up hasn't occurred at this site, but batch injection successful, area of influence determined in Section 4.3.6.1. Scale-up issues and cost implications are discussed in Section 6.3 and in Section 5.7 of the protocol document (Suthersan, 2002)
SECONDARY CRITERIA (Performance Objectives) (Quantitative)			
Geochemistry Manipulation	DO to <1 mg/L ORP <50 mV	Performance monitoring data evaluated before each injection event	An anaerobic environment was created within the reactive zone (see Section 4.3.7.2)
Contaminant Mobility	Presence of "spike" in concentration after initial injections	CAH data for wells IRZ-1, RAP1-6T	Spikes observed in TCE and cis-DCE concentrations shortly after first injection (see Section 4.3.7.2)
Contaminant Reduction (Rate)	Calculate k	K determined from long-term pre-demonstration data at RAP1-6T and from data trends at IRZ-1 and RAP1-6T	Calculated k (see Section 4.3.3.5)
Hazardous Materials	Potentially hazardous materials limited to soil cuttings from well drilling and purge water	Field records, analyses of soil cuttings	Purge water disposed of in on-site wastewater treatment system, cuttings from soil borings characterized and disposed of off-site

Table 4-3. Bromide Tracer Data Summary

	2000		2001										2002				
Well ID	**6/15**	**11/7**	**1/4**	**1/11**	**1/31**	**3/26**	**4/7**	**5/4**	**7/11**	**10/12**	**10/30**	**11/19**	**1/23**	**2/22**	**3/27**	**9/16**	**10/15**
IRZ-1	<0.027	0.14	NS	0.17	0.21	0.85	13.7	4.1	1.2	0.54	NS	0.22	0.2	<0.027	0.28	0.54	0.72
IRZ-2	<0.027	0.16	NS	NS	<0.027	NS	0.15	0.14	0.12	<0.027	0.082	0.08	<0.027	<0.027	0.14	NS	<0.027
IRZ-3	<0.027	0.15	NS	NS	<0.027	NS	0.16	<0.027	<0.027	<0.027	NS	0.095	0.11	<0.027	<0.027	NS	<0.027
IRZ-4	<0.027	0.16	NS	0.14	<0.027	NS	<0.027	<0.027	<0.027	<0.027	NS	0.091	0.16	NS	0.071	<0.027	0.096
IRZ-5	NS	NS	NS	NS	NS	NS	NS	<0.027	<0.027	0.092	NS	0.09	0.1	<0.027	0.12	0.12	0.23
RAP1-6T	<0.027	0.14	0.17	0.18	0.3	41.3	21.4	5.1	1.4	0.12	NS	0.086	0.13	<0.027	0.34	0.21	0.19
RAP1-6R	0.11	0.12	NS	NS	NS	NS	<0.027	0.13	<0.027	NS	NS	0.077	NS	NS	<0.027	NS	0.1
RAP1-6S	<0.027	<0.027	NS	NS	NS	NS	<0.027	<0.027	<0.027	NS	NS	0.1	NS	NS	0.12	NS	1.6
B239-MW	<0.027	<0.027	NS	NS	<0.027	NS	<0.027	<0.027	<0.027	NS	NS	<0.027	NS	NS	<0.027	NS	<0.027

NS = Not Sampled

Results in units of mg/L

Table 4-4. Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD)

Constituent	Date	B239-MW	RAP1-6R	RAP1-6S	IRZ-INJ	RAP1-6T	IRZ-1	IRZ-4	IRZ-2	IRZ-3	IRZ-5
BOD (mg/l)	06/16/00	3 U	3 U	3 U	3 U	3 U	3 U	3 U	3 U	3 U	NA
	05/07/01	3 U	3 U	3 U	10800	280	320	3 U	3 U	3 U	3.6
	10/15/02	2 U	24	160	14000	58	140	2 U	2 U	2 U	10
COD (mg/l)	06/16/00	106	20 U	20 U	26.9	52.1	23.3	55.7	120	70.1	NA
	05/07/01	20 U	20 U	20 U	12900	308	367	20 U	20 U	20 U	20 U
	10/15/02	20 U	52	360	51000	115	250	20 U	20 U	20 U	40

Notes:
Analytical methods: BOD by SW846 Method 405.1/5210B, COD by SW846 Method 410.4
NA = Not analyzed
U = Undetected at the listed detection limit

Table 4-5. Data from Initial Groundwater Sampling Round at Hanscom AFB

Analyte	Units	B239	IRZ-INJ	IRZ-INJ-DUP	RAP1-6R	RAP-6T	IRZ-1	IRZ-4	IRZ-3	IRZ-2	RAP1-6S
Trichloroethene	ug/L	29	560	530	1400	810	1100	1500	1300	1900	1.4
cis-1,2-Dichloroethene	ug/L	70	1600	1600	4300	2100	3500	5300	4400	5300	3.8
trans-1,2-Dichloroethene	ug/L	0.88	16	16	22	21	23	ND	27	27	ND
1,1-Dichloroethene	ug/L	1.7	48	47	130	72	130	ND	140	170	ND
Vinyl chloride	ug/L	16	360	370	690	660	1100	1100	860	1300	ND
1,1-Dichloroethane	ug/L	4.8	110	98	240	130	210	350	280	330	ND
Ethane	ug/L	0.02	1.31	1.18	0.36	0.5	2.13	10.15	3.37	3.02	ND
Ethene	ug/L	0.61	24.73	22.91	30.57	25.85	45.24	96.41	71.32	66.83	0.02
Dissolved Oxygen	mg/L	1.38	1.19	---	1.48	0.43	0.47	0.5	0.61	0.47	0.35
Oxygen - Lab	mg/L	0.19	0.72	0.85	2.72	2.96	1.13	0.86	1.12	0.16	2.47
Oxidation Reduction Potential	mv	-32.1	200	---	-57.5	2.9	14	-30	-16	-38	-21.4
pH	SU	6	5.79	---	7.1	5.9	6.03	6.28	6.17	6.3	5.73
Conductance	uS/cm	33	356	---	16	37	445	512	501	472	48
Dissolved Organic Carbon	mg/l	3.7	1.8	2	2.2	2.5	2.8	3.5	3.4	3.3	1.4
Total Organic Carbon	mg/l	2	1.9	1.9	1.8	6.2	2.8	3.5	3.3	3.3	1.8
Chemical Oxygen Demand	mg/l	106	30.5	23.3	ND	52.1	23.3	55.7	70.1	120	ND
Biochemical Oxygen Demand	mg/l	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Nitrate as N	mg/L	ND	0.04	ND	ND	ND	ND	ND	ND	ND	2.1
Nitrite as N	mg/L	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Ammonia as N	mg/L	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Total Manganese-Field	mg/L	0	0	---	0.2	0.3	0.3	0.6	0	0.3	0
Dissolved Manganese-Field (mg/l)	mg/L	0	0	---	0.3	0.3	0	0.3	0	0.3	0
Ferrous Iron - Field	mg/L	>10	0.4	---	0.4	>10	5	>10	>10	>10	>10
Unfiltered Iron - Lab	mg/L	24.6	1.4	1.4	0.71	9.1	9.2	16.6	24.3	20	3.8
Dissolved Iron - Field	mg/L	>10	0.1	---	0.4	4	5	>10	>10	>10	0.3
Dissolved Iron - Lab	mg/L	23.4	0.31	0.31	0.15	5.5	8.6	12.3	14	12.3	0.74
Bromide	mg/L	ND	ND	ND	0.11	ND	ND	ND	ND	ND	ND
Chloride	mg/L	9.2	14.7	14.8	17.1	17	18.6	23.6	21.8	21.1	1.6
Sulfate	mg/L	38.9	32.3	32.2	22.8	29.4	28.3	22.7	24.2	21.5	21.6
Sulfide - Field	mg/L	0	0	---	0	0	0	0	0	0	0.1
Carbon Dioxide	mg/L	86.2	78	80.9	9.4	74.9	62.2	47.3	67.6	38.5	50.2
Methane	ug/l	15	63.5	58.1	72.2	51.5	84	138.8	130.1	122.2	1.4
Hydrogen	nM/L	1.6	>50	>50	5.2	>50	---	>50	>50	>50	>50
Nitrogen	mg/L	11.1	13.1	12.5	14.7	17.5	14.8	14.5	17.3	14.1	10.8

ND - Not Detected

Table 4-6. Data from Midpoint Groundwater Sampling Round at Hanscom AFB, 05-03-01 to 05-08-01

Analyte	Units	B239	IRZ-INJ	RAP1-6R	RAP1-6T	IRZ-1	IRZ-4	IRZ-5	IRZ-3	IRZ-2	RAP1-6S	RAP1-6S-Dup
Trichloroethene	ug/L	22	15	1300	4.7	0.7	1200	1200	320	1300	1.7	1.7
cis-1,2-Dichloroethene	ug/L	54	640	4600	3000	3600	4900	4600	5000	5700	6.4	6.4
trans-1,2-Dichloroethene	ug/L	0.68	3.1	34	23	39	44	36	38	34	ND	ND
1,1-Dichloroethene	ug/L	1.3	9	140	110	91	160	170	140	160	0.12	0.12
Vinyl chloride	ug/L	9	67	690	640	630	990	970	820	870	0.45	0.47
1,1-Dichloroethane	ug/L	3.3	24	250	140	170	270	280	240	290	0.18	0.18
Ethane	ug/L	0.02	0.35	0.25	0.47	0.62	0.63	0.79	0.72	0.77	ND	ND
Ethene	ug/L	0.36	2.3	22	22	34	41	36	51	46	0.03	0.02
Dissolved Oxygen-Field	mg/L	0	1.35	0	0	0	0	0	0	0	0.58	NA
Oxygen-Lab	mg/L	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Oxidation Reduction Potential	mv	22	-63	32	-190	-175	-66	-9	-87	-47	270	NA
pH	SU	5.7	4.72	6.46	6.83	6.84	6.59	5.95	6.44	6.31	4.51	NA
Conductance	uS/cm	204	4000	224	1040	1130	269	258	306	256	65	NA
Alkalinity	mg/L	70.7	673	99	299	368	120	86.9	156	104	7.1	7.1
Dissolved Organic Carbon	mg/L	2.2	4680	2.6	131	143	3.6	4.2	3.6	3.2	1.5	1.7
Total Organic Carbon	mg/L	2.1	5840	2.1	186	201	3.5	3.5	3.6	3.2	1.5	1.5
Chemical Oxygen Demand	mg/L	ND	12900	ND	308	367	ND	ND	ND	ND	ND	ND
Biochemical Oxygen Demand	mg/L	ND	10800	ND	280	320	ND	3.6	ND	ND	ND	ND
Nitrate as N	mg/L	ND	ND	ND	0.2	0.25	ND	ND	ND	ND	1.5	1.5
Nitrite as N	mg/L	ND	17.4	ND	ND	0.27	ND	ND	ND	ND	ND	ND
Ammonia as N	mg/L	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Soluble Manganese-Field	mg/L	0.3	NA	1	>2	>2	0.3	0.3	0	0	0	0
Dissolved Manganese-Lab	mg/L	1.3	21.2	1.4	6.9	5.9	0.93	0.77	0.93	0.79	0.076	0.078
Total Managanese-Lab	mg/L	1.3	21.1	1.4	6.9	6.1	0.97	0.8	0.99	0.91	0.078	0.077
Total Iron - Field	mg/L	>10	>10	0.2	>10	>10	>10	>10	>10	>10	0.7	0.7
Total Iron - Lab	mg/L	26.4	730	0.14	141	141	14.4	11	24.8	28.9	0.51	0.5
Dissolved Iron-Field	mg/L	>10	>10	0	>10	>10	>10	>10	>10	8	0.4	0.4
Dissolved Iron-Lab	mg/L	25.9	729	ND	142	135	13	9.7	21.8	9.2	0.39	0.41
Bromide	mg/L	ND	ND	0.13	5.1	4.1	ND	ND	ND	0.14	ND	ND
Chloride	mg/L	6.8	253	19.7	23.3	26.9	21.8	22.7	19.7	19.8	1.8	1.8
Total Dissolved Solids	mg/L	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Sulfate	mg/L	43.7	30.1	21.7	3.6	0.22	23.2	27.4	10.9	21.8	18.9	19.7
Hydrogen Sulfide - Field	mg/L	0	5	0	1	0	0.1	0.1	0	0.3	0	0
Carbon Dioxide	mg/L	106.8	1149.7	14.8	99.1	86	60.3	57.6	54.1	50.5	74.2	79.7
Methane	ug/L	3.6	5.8	51.1	106.5	ND	74.2	72.8	92.8	86.3	3.3	3.9
Hydrogen	nM/L	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Nitrogen	mg/L	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

NA = NOT ANALYZED
ND = NON DETECT

Table 4-7. Data from Midpoint Groundwater Sampling Round at Hanscom AFB, October 2002

Analyte	Units	B239	IRZ-INJ	RAP1-6R	RAP-6T	RAP1-6T-DUP	IRZ-1	IRZ-4	IRZ-5	IRZ-3	IRZ-2	RAP1-6S
Trichloroethene	ug/L	39	ND	1400	510	530	68	1400	1100	1400	1800	0.4
cis-1,2-Dichloroethene	ug/L	88	110	4900	3300	3300	980	5000	4400	4800	5100	1.6
trans-1,2-Dichloroethene	ug/L	1	ND	ND	34	30	26	ND	33	40	36	ND
1,1-Dichloroethene	ug/L	2.1	ND	130	87	84	23	160	140	ND	180	ND
Vinyl chloride	ug/L	16	ND	980	1000	980	650	1100	1100	1100	1200	0.35
1,1-Dichloroethane	ug/L	5.4	ND	240	180	190	190	250	240	250	290	ND
Ethane	ug/L	0.02	0.01	0.36	0.24	NA	0.38	0.57	0.83	0.61	0.8	0.12
Ethene	ug/L	0.52	0.16	37.21	133.09	NA	1107.96	41.4	83.94	45.9	45.63	0.09
Dissolved Oxygen-Field	mg/L	0.34	0.36	0.44	1.65	NA	0.58	7.67	0.93	0.37	1.04	2.59
Oxygen-Lab	mg/L	0.56	0.21	0.29	0.2	NA	ND	0.52	0.87	0.17	0.19	0.41
Oxidation Reduction Potential	mv	-15	-147	-226	-169	NA	-175	-75	-86	-96	-81	-49
pH	SU	6.26	4	6.92	6.6	6.6	7.11	6.7	6.7	6.73	6.6	6.2
Conductance	uS/cm	216	5910	310	401	NA	616	286	308	317	271	385
Alkalinity	mg/L	54	ND	120	160	170	210	120	140	110	110	200
Dissolved Organic Carbon	mg/L	2	13000	13	36	39	74	2.5	12	2.4	2.3	130
Total Organic Carbon	mg/L	1.3	13000	15	33	38	77	2.6	10	2.4	2.3	110
Chemical Oxygen Demand	mg/L	ND	51000	52	100	130	250	ND	40	ND	ND	360
Biochemical Oxygen Demand	mg/L	ND	14000	24	56	59	140	ND	10	ND	ND	160
Nitrate as N	mg/L	ND	ND	0.018	ND	ND	ND	ND	ND	ND	ND	0.11
Nitrite as N	mg/L	ND	ND	0.05	ND	ND	ND	ND	ND	ND	ND	ND
Ammonia as N	mg/L	0.72	2.7	3.5	0.3	0.3	0.44	0.2	0.2	0.23	0.25	0.63
Soluble Manganese-Field	mg/L	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Dissolved Manganese-Lab	mg/L	NA	1.7	1.9	1.7	1.7	1.8	0.86	0.91	0.68	0.73	1.1
Total Managanese-Lab	mg/L	NA	1.7	1.7	1.6	1.6	1.8	0.96	0.91	0.73	0.75	1.2
Total Iron - Field	mg/L	1	50	<25	25	NA	50	NA	NA	<25	NA	50
Total Iron - Lab	mg/L	NA	220	0.33	54	56	91	19	16	15	17	160
Dissolved Iron-Field	mg/L	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Dissolved Iron-Lab	mg/L	NA	220	0.32	59	59	88	13	16	23	13	140
Bromide	mg/L	ND	58	0.1	0.2	0.18	0.72	0.096	0.23	0.027	ND	1.6
Chloride	mg/L	2.7	120	16	24	24	33	3.1	2.6	22	15	3.4
Total Dissolved Solids	mg/L	130	15000	190	260	280	360	210	220	210	190	400
Sulfate	mg/L	36	890	20	13	13	2.3	23	22	23	22	17
Hydrogen Sulfide - Field	mg/L	0	0.7	0.3	1	NA	0	0.5	NA	0	NA	0.5
Carbon Dioxide	mg/L	64.3	1327.5	19.8	41.1	NA	19.7	58.2	45.4	57.7	46.5	175.6
Methane	ug/L	16.1	31.7	68.4	983.7	NA	2057.7	80.6	117.1	95.8	94.2	1845.3
Hydrogen	nM/L	495.6	1514	157.7	134.1	NA	1452.4	620.9	179.6	423.5	667.8	367.4
Nitrogen	mg/L	9.8	1.2	13.9	10.3	NA	8.7	14.2	15.9	15	15.6	13.6

NA = NOT ANALYZED
ND = NON DETECT

Table 4-8. Reductive Dechlorination Processes

PROCESS	PCE	TCE	c-DCE	VC	TCA	DCA	CT	CF	DCM
Direct Aerobic	N	N	Y&N	Y	N	N	N	N	Y
Cometabolic w/ CH_4	N	Y	Y	Y	Y&N	N*	N	Y	NR
Cometabolic w/ toluene	N	Y	Y	Y	N	N*	N	Y&N	NR
Cometabolic w/ NH_4	N	Y	Y	Y	Y	N*	N	Y	NR
Direct Anaerobic	N	N	N	Y	N	N	N	N	Y
Anaerobic/ Denitrification	Y&N	Y&N	N*	N*	N*	N*	Y	Y&N	NR
Anaerobic/Sulfate reduction	Y	Y	Y	Y	Y	Y	Y	Y	NR
Anaerobic/ Methanogenic	Y	Y	Y	Y	Y	Y	Y	Y	NR

N: Not documented in the literature
Y: Documented in the literature many times; concensus opinion
Y&N: Documented in the literature more than once of both occurrence and absence
N*: Not documented in the literature to date, but not investigated significantly
NR: Process may occur but Not Relevant since competing process occurs more rapidly

Source: ITRC 2002, ITRC 1999

Key

Carbon Tetrachloride	CT
Chloroform	CF
Dichloromethane	DCM
1,1,1-Trichloroethane	TCA
Dichloroethane	DCA
Tetrachloroethene	PCE
Trichloroethene	TCE
cis-1,2-Dichloroethene	*c*-DCE
Vinyl chloride	VC

Table 4-9. Summary of Biodegradation Rates over Selected Time Intervals

		Pre-Treatment			During Treatment			Other ERD Sites*		Published NA Rates	
Constituent	**Well**	**k (1/yr)**	**R^2**	**Half Life (days)**	**k (1/yr)**	**R^2**	**Half Life (days)**	**k (1/yr)**	**Half Life (days)**	**k (1/yr)**	**Half Life (days)**
TCE	IRZ-Inj				3.16	0.7093	80	0.98	257	0.15-2.58	98-1653
	IRZ-1				8.98	0.6632	28	3.95	64		
	RAP1-6T	-0.07	0.3638	(Gain)	5.12	0.4726	49	3.10	82		
								2.33	108		
								1.31-3.20	79-193		
								1.83-8.40	30-139		
								15.33	17		
cis-DCE	IRZ-Inj				0.59	0.4035	428	2.45	103	0.35-2.26	112-720
	IRZ-1				0.92	0.0590	275	3.18	80		
	RAP1-6T	3E-03	0.0010	97287	1.14	0.7348	223	2.15	117		
								1.26	200		
								1.46-6.21	41-173		
								15.33	17		
Vinyl Chloride	IRZ-Inj				2.33	0.8910	109	2.92	87	0.35-2.26	112-720
	IRZ-1							0.95	267		
	RAP1-6T	-0.04	0.3050	(Gain)				0.69	365		
								1.10-5.48	46-231		

Notes:

See Figures 4-62 through 4-64 for illustration of selected intervals over which rates were calculated

Rates calculated for other ARCADIS ERD sites, as published in Horst et al. (2000) and Suthersan et al. (2002)

Published data are anaerobic, aqueous biodegradation half-lives from Howard et al. (1991), assumed to represent natural attenuation

Table 4-10. Total Dissolved Solids (TDS) in Groundwater

Well	**TDS (mg/l)**
HAN-GW-B239	130
HAN-GW-RAP1-6S	400
HAN-GW-RAP1-6R	190
HAN-GW-IRZ-INJ	15000
HAN-GW-RAP1-6T	260
HAN-GW-RAP1-6T DUP	280
HAN-GW-IRZ-1	360
HAN-GW-IRZ-4	210
HAN-GW-IRZ-2	190
HAN-GW-IRZ-3	210
HAN-GW-IRZ-5	220
HAN-GW-B242	150

Notes:

Samples collected October 14-16, 2002

Analytical method: SW846 Method 160.1

Shading indicates exceedance of the Federal Secondary Drinking Water Standard of 500 mg/l for TDS

Table 4-11. VOCs of Secondary Concern

Constituent	Standard		Well	Date	Result (ug/L)
Acetone	610	PRG	HAN-GW-IRZ-1	05/07/01	38
			HAN-GW-RAP1-6S	10/15/02	47
2-Butanone (MEK)	1900	PRG	HAN-GW-IRZ-1	05/07/01	240 E
			HAN-GW-RAP1-6S	10/15/02	34
			HAN-GW-RAP1-6T	05/07/01	180 E
Carbon tetrachloride	5	MCL	HAN-GW-RAP1-6S	10/15/02	0.11 J
Chloroform	80	MCL	HAN-GW-IRZ-INJ	05/08/01	8.6
				10/15/02	18 J
1,2-Dibromoethane (EDB)	0.05	MCL	HAN-GW-IRZ-5	10/16/02	6.1 J
Dichlorodifluoromethane	390	PRG	HAN-GW-IRZ-1	10/14/02	9.4 J
2-Hexanone	1500	RBC	HAN-GW-IRZ-5	10/16/02	79 J
Methylene chloride (Dichloromethane)	5	MCL	HAN-GW-IRZ-3	06/15/00	0.53 J
				05/03/01	0.21 J,B
				10/15/02	8.4 J,B
			HAN-GW-IRZ-4	05/04/01	0.36 J,B
			HAN-GW-IRZ-INJ	06/16/00	0.55 J
			HAN-GW-RAP1-6R	06/15/00	0.57 J
				05/07/01	0.3 J,B
				10/15/02	8.1 J,B
4-Methyl-2-pentanone (MIBK)	160	PRG	HAN-GW-IRZ-5	10/16/02	70 J
Methyl t-butyl ether (MTBE)	13	PRG	HAN-GW-RAP1-6S	10/15/02	1.3 J
Styrene	100	MCL	HAN-GW-IRZ-INJ	05/08/01	0.51 J

(continued on next page)

Table 4-11. (continued)

Constituent	Standard	Well	Date	Result (ug/L)
Toluene	1000 MCL	HAN-GW-B239	05/03/01	0.21
		HAN-GW-IRZ-1	06/16/00	0.59 J
			05/07/01	0.34 J
		HAN-GW-IRZ-2	06/15/00	2.1 J
			05/04/01	2.3
		HAN-GW-IRZ-3	06/15/00	0.92 J
			05/03/01	0.97 J
		HAN-GW-IRZ-4	06/15/00	1.2
			05/04/01	1.4
		HAN-GW-IRZ-5	05/08/01	2.8
		HAN-GW-IRZ-INJ	06/16/00	0.54 J
			05/08/01	0.66 J
		HAN-GW-IRZ-INJ-DUP	06/16/00	0.7 J
		HAN-GW-RAP1-6R	05/07/01	3
		HAN-GW-RAP1-6S	10/15/02	0.45 J
		HAN-GW-RAP1-6T	05/07/01	1
		HAN-GW-RAP1-6T DUP	10/14/02	12 J
1,2,3-Trichloropropane	0.0056 PRG	HAN-GW-IRZ-5	10/16/02	26
Xylenes, Total	10000 MCL	HAN-GW-IRZ-1	05/07/01	0.4 J
		HAN-GW-IRZ-2	06/15/00	3.9
			05/04/01	2.6
		HAN-GW-IRZ-3	06/15/00	1.4
			05/03/01	0.98 J
		HAN-GW-IRZ-4	06/15/00	4.4
			05/04/01	2.2
		HAN-GW-IRZ-5	05/08/01	1.5
		HAN-GW-RAP1-6S	10/15/02	0.57 J
		HAN-GW-RAP1-6T	05/07/01	0.56
		HAN-GW-RAP1-6T DUP	10/14/02	18 J,B

Notes:
Analytical method - SW846 Method 8260
B = Detected in blank
E = Estimated
J = Estimated
MCL - Federal Maximum Contaminant Level for drinking water
PRG - US EPA Region 9 Preliminary Remedial Goal for tap water (provided where no MCL exists)
RBC - US EPA Region 3 Risk-Based Concentration for tap water (provided where no MCL or PRG exists)
Shading indicates exceedance of listed standard
Only detected compounds listed; chlorinated ethenes and ethanes not included

Table 4-12. Total Metals in Groundwater

Constituent (mg/l)	MCL or other Std.	B-239		IRZ-INJ		RAP1-6R		RAP1-6S		RAP1-6T		RAP1-6T DUP		IRZ-1		IRZ-4		IRZ-2		IRZ-3		IRZ-5		B-242		FB	
Antimony	0.006	0.02	U	0.0086	B	0.02	U	0.02	U	0.02	U	0.02	U	0.02	U	0.02	U	0.02	U	0.02	U	0.02	U	0.02	U	0.02	U
Arsenic	0.045 (PRG)	0.012		0.049		0.01	U	0.092		0.023		0.02		0.042		0.0083	B	0.011		0.031		0.01		0.01	U	0.01	U
Beryllium	0.004	0.004	U	0.0076		0.004	U	0.004	U	0.004	U	0.004	U	0.004	U	0.004	U	0.004	U	0.004	U	0.004	U	0.004	U	0.004	U
Cadmium	0.005	0.005	U	0.0019	B	0.005	U	0.005	U	0.005	U	0.005	U	0.005	U	0.005	U	0.005	U	0.005	U	0.005	U	0.005	U	0.005	U
Chromium	0.1	0.0033	B	0.2		0.0037	B	0.003	B	0.0022	B	0.0065	B	0.01	U	0.072		0.01	U	0.0049	U	0.01	U	0.015		0.01	U
Copper	1.3	0.006	B	0.22		0.0016	B	0.002	B	0.0015	B	0.0016	B	0.0017	B	0.0093	B	0.0009	B	0.0026	B	0.02	U	0.0017	B	0.0016	B
Iron	11 (PRG)	19		220		0.33		160		54		56		91		19		17		23		16		4.1		0.05	U
Lead	0.015	0.005	U	0.028		0.005	U	0.005	U	0.005	U	0.005	U	0.005	U	0.0041	B	0.005	U	0.005	U	0.005	U	0.0019	B	0.005	U
Manganese	0.88 (PRG)	1.0		1.7		1.7		1.2		1.6		1.6		1.8		0.96		0.75		0.73		0.91		0.12		0.01	U
Mercury	0.002	0.0002	U	0.0012	U	0.0002	U	0.0002	U	0.0002	U	0.0002	U	0.0002	U	0.0002	U	0.0002	U	0.0002	U	0.0002	U	0.0002	U	0.0002	U
Nickel	0.73 (PRG)	0.0082	B	0.25		0.04	U	0.04	U	0.04	U	0.0071	B	0.04	U	0.049		0.04	U	0.0059	U	0.04	U	0.026	B	0.04	U
Selenium	0.05	0.01	U	0.011		0.01	U	0.01	U	0.01	U	0.01	U	0.01	U	0.01	U	0.01	U	0.01	U	0.01	U	0.01	U	0.01	U
Silver	0.18 (PRG)	0.01	U	0.01	U	0.01	U	0.01	U	0.01	U	0.01	U	0.01	U	0.01	U	0.01	U	0.01	U	0.01	U	0.01	U	0.01	U
Thallium	0.002	0.01	U	0.02	U	0.01	U	0.012		0.01	U	0.01	U	0.01	U	0.01	U	0.01	U	0.01	U	0.01	U	0.01	U	0.01	U
Zinc	11 (PRG)	0.11		0.7		0.0063	B	0.0072	B	0.02	U	0.02	U	0.02	U	0.016	B	0.02	U	0.0077	U	0.02	U	0.088		0.02	U

Notes:
Samples collected October 14-16, 2002
Analytical methods - SW846 Methods 6010B and 7470
B = Detected in blank
U = Undetected at the detection limit listed
MCL - Federal Maximum Contaminant Level for drinking water
PRG - US EPA Region 9 Preliminary Remedial Goal for tap water (provided where no MCL exists)
Shading indicates exceedance of listed standard

Table 4-13. Dissolved Metals in Groundwater

Constituent (mg/l)	MCL or other Std.	B-239	IRZ-INJ	RAP1-6R	RAP1-6S	RAP1-6T	RAP1-6T DUP	IRZ-1	IRZ-4	IRZ-2	IRZ-3	IRZ-5	B-242	FB
Antimony	0.006	0.02 U	0.0056 B	0.02 U	0.02 U	0.02 U	0.02 U	0.02 U	0.02 U	0.02 U	0.02 U	0.02 U	0.02 U	0.02 U
Arsenic	0.045 (PRG)	0.0041 B	0.051	0.01 U	0.079	0.022	0.024	0.04	0.0062 B	0.0051 B	0.0077 B	0.0082 B	0.01 U	0.01 U
Beryllium	0.004	0.004 U	0.0077	0.004 U	0.004 U	0.004 U	0.004 U	0.004 U	0.004 U	0.004 U	0.004 U	0.004 U	0.004 U	0.004 U
Cadmium	0.005	0.005 U	0.0023 B	0.005 U	0.005 U	0.005 U	0.005 U	0.005 U	0.005 U	0.005 U	0.005 U	0.005 U	0.005 U	0.005 U
Chromium	0.1	0.01 U	0.19	0.0023 B	0.01 U	0.01 U	0.01 U	0.01 U	0.01 U	0.01 U	0.01 U	0.01 U	0.01 U	0.01 U
Copper	1.3	0.0018 B	0.17	0.0013 B	0.0011 B	0.0012 B	0.0013 B	0.0012 B	0.02 U	0.02 U	0.02 U	0.02 U	0.02 U	0.0016 B
Iron	11 (PRG)	19	220	0.32	140	59	59	88	13	13	15	16	4.4	0.05 U
Lead	0.015	0.005 U	0.027	0.005 U	0.005 U	0.005 U	0.005 U	0.005 U	0.005 U	0.005 U	0.005 U	0.005 U	0.0017 B	0.005 U
Manganese	0.88 (PRG)	1.0	1.7	1.9	1.1	1.7	1.7	1.8	0.86	0.73	0.68	0.91	0.13	0.01 U
Mercury	0.002	0.0002 U	0.0012 U	0.0002 U	0.0002 U	0.0002 U	0.0002 U	0.0002 U	0.0002 U	0.0002 U	0.0002 U	0.0002 U	0.0002 U	0.0002 U
Nickel	0.73 (PRG)	0.0058 B	0.25	0.04 U	0.04 U	0.04 U	0.04 U	0.04 U	0.04 U	0.04 U	0.04 U	0.04 U	0.016 B	0.04 U
Selenium	0.05	0.01 U	0.017	0.01 U	0.01 U	0.01 U	0.01 U	0.01 U	0.01 U	0.01 U	0.01 U	0.01 U	0.01 U	0.01 U
Silver	0.18 (PRG)	0.01 U	0.01 U	0.01 U	0.01 U	0.01 U	0.01 U	0.01 U	0.01 U	0.01 U	0.01 U	0.01 U	0.01 U	0.01 U
Thallium	0.002	0.01 U	0.01 U	0.01 U	0.014	0.01 U	0.01 U	0.01 U	0.01 U	0.01 U	0.01 U	0.01 U	0.01 U	0.01 U
Zinc	11 (PRG)	0.043	0.71	0.02 U	0.0066 B	0.02 U	0.02 U	0.02 U	0.02 U	0.02 U	0.02 U	0.0069 B	0.032	0.02 U

Notes:
Samples collected October 14-16, 2002
Analytical methods - SW846 Methods 6010B and 7470
B = Detected in blank
U = Undetected at the detection limit listed
MCL - Federal Maximum Contaminant Level for drinking water
PRG - US EPA Region 9 Preliminary Remedial Goal for tap water (provided where no MCL exists)
Shading indicates exceedance of listed standard

Table 4-14. Molasses Analysis for Inorganics

Blackstrap Molasses Analysis (US Sugar Corp., 2000)	
Weight/gallon	12.0 lbs
Calcium	0.80%
Chloride	2.10%
Cobalt	negligible
Copper	14 ppm
Iron	130 ppm
Magnesium	0.27%
Manganese	5 ppm
Nitrogen	1.01%
Phosphorus	negligible
Potassium	4.20%
Selenium	negligible
Sodium	0.09%
Sulfur	0.78%
Zinc	8 ppm

from http://www.suga-lik.com/molasses/molasses_frame.html

Table 4-15. Molasses-Water Analysis for Inorganics

		Laboratory	Laboratory Analysis	
Constituent	**SDWA MCL**	**Detection Lmt**	**Mixture**	**Qualifier**
Molasses used at a commercial site in Ohio; 10:1 water:molasses mixture				
Arsenic	0.05	0.01	0.0088	B
Barium	2	0.2	0.031	B
Cadmium	0.005	0.005	0.00053	BJ
Lead	--	0.003	0.005	
Chromium	0.1	0.01	0.0078	B
Selenium	0.05	0.005	0.028	B
Silver	0.1*	0.01	<0.01	
Mercury	0.002	0.0002	0.000077	B
Molasses used at Hanscom; 9:1 water:molasses mixture (October 2002)				
Chloride	250*		1500	

Concentrations reported in milligrams per liter

Metals analysis conducted by USEPA Method 6010B

Laboratory Qualifiers:

"B" - Estimated result below laboratory method detection limit

"J" - Method blank contamination, associated method blank contains the target analyte at a reportable level

Federal Standards are SDWA MCLs or *secondary drinking water regulations

Arsenic MCL is currently 0.05 mg/L and will change to 0.01 mg/L In 2006

Table 4-16. Fatty Acids in the October 2002 Full Monitoring Round

Well	Date	Pyruvic	Lactic	Formic	Acetic	Propionic	Butyric
IRZ-1	10/14/2002	<4	<1	<1	111.4	17.5	14.1
RAP1-6T	10/14/2002	<4	<1	<1	57.3	5.9	6.6
MW-B239	10/14/2002	<4	<1	<1	<1	<1	<1

Results reported in mg/L

Table 4-17. Comparison of Technology Alternatives

	Groundwater Pump & Treat	Aquifer Sparging
Effectiveness		
	Rapid results (containment & mass removal) once system is deployed.	Rapid results (containment & mass removal) once system is deployed.
	Effective at mass removal of contaminants.	Effective at mass removal of contaminants.
	Very effective for hydraulic containment & easily demonstrated.	Effectiveness for containment and/or plume treatment is more complex to demonstrate in short-term.
	Not effective in meeting all but the least stringent clean-up goals.	In-situ treatment allows for more effective treatment of organics suchs as VOCs. However, overall effectivness limited to compounds with high Henry's Law constant or those that can degrade aerobically.
Reliability		
	Moderate reliability - number of fixed/engineered components increase likelihood of operational problems/failures.	In-situ nature and limited fixed components make technology very reliable.
	Fixed, engineered nature of systems severely limit flexibility and adaptability.	Fixed, engineered nature of systems severely limit flexibility and adaptability.
	Operational experience suggests systems can be plauged by reliability problems associated with non-target contaminants (ie, fouling).	More reliable than ex-situ treatment techniques given no need to handle extracted groundwater.
	Can address wide range of contaminants (VOCs, SVOCs, metals, other inorganics, etc.).	Limited suite of compounds that can be reliable treated (see above).
Speed		
	Short-term - Slow speed. Fairly complex design, approval & permitting process needed for implementation.	Short-term - Moderate speed. Reasonable design & approval, limited permitting process needed for implementation.
	Long-term - Poor speed. Nature of technology requires very long time to reach closure.	Long-term - Moderate speed. Nature of technology requires some time to reach closure - especially if goals are low.
Ease of Use		
	Technology is very complex due to water handling, energy requirments, manpower requirements, and residuals management.	Technology is moderately complex due to energy requirments, manpower requirements. Limited residuals management.
	Health & safety concerns are moderate. Technology can cause additional routes of exposure to media.	Health & safety concerns are low. Technology does not provide additional routes of exposure to media.
	Abive grade nature of treatment system can impact Site activities and/or development potential.	Abive grade nature of treatment system can impact Site activities and/or development potential.

(continued)

Table 4-17. (concluded)

Chemical Oxidation	Enhanced Reductive Dechlorination
Effectiveness	**Effectiveness**
Very rapid results (mass removal) upon application of technology. Effective at mass removal of contaminants. Effectiveness for simple to demonstrate in short-term. Long-term monitoring required to evaluate 'rebound'	Technology will provide effective mass removal upon acclimitixation of reactive zone. Effective at mass removal of contaminants. Effectiveness for containment and/or plume treatment is more complex to demonstrate in short-term.
In-situ treatment allows for more effective treatment of organics suchs as VOCs. However, overall effectivness limited to organic compounds. In addition, mixed organic plumes may require multiple oxidants.	In-situ treatment allows for more effective treatment of organics suchs as VOCs and others. Technology can also be used to treat other compounds including metals.
Reliability	**Reliability**
In-situ nature and no fixed components make technology very reliable. Lack of fixed, engineered systems make technology flexible & adaptable.	In-situ nature and no fixed components make technology very reliable. Lack of fixed, engineered systems make technology flexible & adaptable.
More reliable than ex-situ treatment techniques given no need to handle extracted groundwater.	More reliable than ex-situ treatment techniques given no need to handle extracted groundwater.
Limited suite of compounds that can be reliable treated (see above).	Larger suite of compounds that can be reliably treated (see above).
Speed	**Speed**
Short-term - Fast speed. Limited design, approval, & permitting process needed for implementation.	Short-term - Fast speed. Limited design, approval, & permitting process needed for implementation.
Long-term - Fast speed. Nature of technology allows for rapid treatment of constituents assuming sufficient oxidant chemical is supplied.	Long-term - Moderate speed. Nature of technology requires some time for reactive zone to fully acclimatize.
Ease of Use	**Ease of Use**
Technology is moderately complex due handling of chemicals and potential for aquifer preparation prior to treatment. However, no residuals management is required.	Technology is very simple to implement. Limited manpower requirements, no residuals management, and no chemical handling concerns.
Health & safety concerns are high. Technology can create high temperature reqctions and/or high levels of oxygen in the subsurface that need to be addressed.	No appreciable health & safety concerns.
Below grade nature of technology and lack of fixed systems limit impacts to Site activities and/or development potential.	Below grade nature of technology and lack of fixed systems limit impacts to Site activities and/or development potential.

Table 5-1. Estimated IRZ Costs for a Hypothetical CAH Plume

WBS Number			DESCRIPTION	QTY	UOM	UNIT COST	COST $
33XXX			**HTRW CONSTRUCTION ACTIVITIES**				
331XX			**HTRW REMEDIAL ACTION (Capital and Operating)**				
	01		**MOBILIZATION AND PREPARATORY WORK**				
	01	01	Mobilization of Construction Equipment (Drilling Rig)	1	EA	$3,000	$3,000
	01	03	Submittals/Implementation Plans/Permits	1	EA	$30,000	$30,000
	01	--	Pilot Testing	1	EA	$75,000	$75,000
	02		**MONITORING, SAMPLING, TESTING, AND ANALYSIS**				
	02	04	Monitoring Wells - Installation	4	EA	$3,000	$12,000
	02	--	Injection Wells - Installation	25	EA	$3,000	$75,000
	02	--	Well Development	1	EA	$4,000	$4,000
	02	--	IDW Disposal (soil cuttings)	1	EA	$1,000	$1,000
	02	05	Sampling Groundwater				
	02	--	Quarterly (10 wells)	4	EA	$5,300	$21,200
	02	--	Semi-Annual (10 wells)	8	EA	$5,300	$42,400
	02	06	Sampling Soil	1	EA	$3,000	$3,000
	02	09	Laboratory Chemical Analysis	12	EA	$3,600	$43,200
	11		**BIOLOGICAL TREATMENT**				
	11	04	In-Situ Biodegradation/Bioreclamation				
	11	--	Trailer-Mounted Molasses Injection System	1	EA	$10,000	$10,000
	11	--	Monthly Molasses Injections - Labor	24	EA	$2,250	$54,000
	11	--	Bi-Monthly Molasses Injections - Labor	18	EA	$2,250	$40,500
	11	--	Field Process Monitoring - Equipment	42	EA	$200	$8,400
	11	--	Field Process Monitoring - Analytical	42	EA	$200	$8,400
	11	--	Laboratory Chemical Analysis (TOC)	100	EA	$30	$3,000
	11	--	Molasses (20 gallons per well per injection)	21000	GAL	$3	$63,000
	11	--	Water for Injection (180 gallons per well per injection)	189000	GAL	$0.0029	$548
	11	--	Well Rehabilitation	63	EA	$300	$18,900
	11	--	Progress Reporting	5	YR	$25,000	$125,000
	11	--	Completion Report	1	EA	$20,000	$20,000
	21		**DEMOBILIZATION**				
	21	--	Well Abandonment	35	EA	$500	$17,500
	--		**INDIRECT ENVIRONMENTAL ACTIVITY COSTS**				
	--	--	Environmental and Safety Training	2	FTE	$250	$500
	--	--	OSHA Ambient Environment Sampling	1	EA	$250	$250
	--	--	Waste Manifesting	1	EA	$500	$500
			TOTAL AMOUNT FOR HYPOTHETICAL SITE				$680,298

Table 5-2. Cost Savings for IRZ Technology Compared to Pump and Treat Systems

Location	Description	Target COCs	Actual/Projected Savings
Rogersville, Tennessee	Parts manufacturing for trucks	PCE, TCA	$200,000
Eastern Tennessee	Fuel facility	PCE, radionuclides	$1,500,000
Chattanooga, Tennessee	Former manufacturing facility	PCE	$500,000 (50%)
Northeastern New Jersey	Pharmaceutical	PCE	$6,000,000
Williamsport, Pennsylvania	Textron/manufacturing	Cr^{+6}, TCE, DCE, VC	$2,250,000 (75%)
Reading, Pennsylvania	Textile equipment	TCE, Cr^{+6}, Pb, Cd	$700,000 (70%)
Emeryville, California	Metal plating manufacturer	TCE, DCE, Cr^{+6}	$1,600,000 (80%)
Hampton, Iowa	Metal plating	Cr^{+6}	$500,000 (66%)
Dallas, Texas	Graphics	Cr^{+6}	$1,500,000 (75%)
Pennsylvania	Lord Corporation	CAHs	$6,400,000 (74%)
East Coast	Metal plating	CAHs, Cr^{6+}	$6,000,000

Table 5-3. Economic Comparison of Probable Costs for Proposed ARCADIS CAH Site in South Carolina

Economic Category		Natural Attenuation	Vacuum-Enhanced Recovery	In-Situ Air Sparging	Iron Reactive Wall	IRZ
Capital						
	Best	$25,000	$350,000	$200,000	$600,000	$150,000
	Worst	$30,000	$500,000	$250,000	$700,000	$160,000
Annual O & M						
	Best	$25,000	$60,000	$45,000	$25,000	$30,000
	Worst	$35,000	$75,000	$60,000	$35,000	$40,000
Present Worth of Total						
	n (years) =	30	20	20	30	15
	Best	$429,000	$1,135,000	$789,000	$1,004,000	$477,000
	Worst	$595,000	$1,481,000	$1,035,000	$1,265,000	$596,000
Total Opinion of Probable Costs						
	Best Case	$400,000	$1,200,000	$750,000	$900,000	$500,000
	Worst Case	$600,000	$1,500,000	$1,100,000	$1,300,000	$800,000

Table 5-4. Results of DuPont Technology Evaluation

Metric	Pump and Treat	Zero-Valent Iron PRB	Substrate Enhanced Biobarrier	Recirculating Source Zone	Natural Attenuation
Present Cost, ($1000s)	$9,800	$3,900	$3,100	$1,300	$890
$/1,000 gallons treated	$8.90	$5.30	$4.20	$1.80	$1.20
$/lb PCE Removed	$1,600	$640	$520	$220	$150

Table 5-5. Summary of IRZ Technology Application Costs

Site	Estimated Capital Costs	Estimated Annual O&M Costs	Actual or Predicted Costs to Closure	Initial Concentration	Dimensions
Industrial Laundry/Dry Cleaning Facility, Eastern PA	$75,000	$45,000	$250,000	46,000 ug/l PCE	10,000 ft^2 x 20 ft deep
Uranium Processing Facility, Eastern US	$480,000	$65,000	$760,000	5 - 14,000 ug/l PCE (plus U)	19.3 acres or 1200 x 700 ft
Former Metal Pating Site, Western US[1]	$100,000	$150,000	$250,000	24,000 ug/l TCE (plus Cr)	< 2 acres or <87,000 ft^2 x 10 feet deep
Industrial Manufacturing Site, South Carolina	$1,400,000	$75,000	$2,000,000	800 ug/l CT, chloroform, TCE	3.25 acres or 141,600 ft^2 x 10 ft deep
Industrial Site, Northeastern US	$150,000	$80,000	$750,000	120 ug/L PCE	3000 ft long in bedrock - depth varies
Former Dry Cleaner, Wisconsin[2]	$200,000	$100,000	$400,000	1,500-4,000 ug/L PCE	30,000 ft^2 x 5 ft deep
Former Automotive Manufacturing Site, Midwestern, US	$75,000	$60,000	$375,000	800 ug/l TCE	1000 x 400 ft x 20 ft deep
AOC 50, Ft. Devens, Ayer, Massachusetts	$150,000	$150,000	NA[3]	4,000 ug/L PCE	3000 x 400 ft x 40 ft deep

Note:

All costs presented in current dollars.

1 - Site has received regulatory closure.

2 - Site has received regulatory closure.

3 - No Predicted Costs to Closure Available. Pilot study ongoing.

List of Appendices

Appendix A-1

IRZ/ERD Bibliography

Appendix A-1: IRZ/ERD Bibliography

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Appendix A-2

Soil Sieve Analyses

ENGINEERING CONSULTING SERVICES, LTD.
Geotechnical • Construction Materials • Environmental

June 8, 2000

Mr. Chris Lutes

Arcadis Geraghty and Miller
4915 Prospectus Dr., Suite F
Durham, NC 27713

RE: Subject: Laboratory Testing
Hanscom AFB Geotechnical Samples
ECS, Ltd. Project Number T7597-A

Dear Mr. Lutes:

This letter of transmittal accompanies the results of the laboratory work you requested for the above referenced project. Five (5) soil samples were tested for particle size distribution in accordance with the American Society of Testing and Materials (ASTM) designations D422. In addition, one sample was selected to split for duplicate testing, bringing the total number of tests run to six (6). All of the samples were classified either as SM, GM, or GP-GM and all contained some material in the gravel as well as silt size range. For purposes of classification, all minus #200 material was assumed to be ML.

Sample HAN-SS-IRZ-1was selected for duplicate testing, and was split for this purpose using a sample splitter, however the presence of gravel sized particles made the resulting quantity of material available marginally small. As a result of this limitation, the classification of this material is different for each of the tests. This is due to the fact that small changes in the number of gravel sized grains has a large effect on the relative grain size distribution.

Customarily, we will hold the remaining portions of these samples for 60 days unless otherwise instructed. Please contact us if you would like any additional testing or if you have any questions.

We appreciate this opportunity to provide our laboratory testing services to you and look forward to serving you again in the near future.

Respectfully,

William L. Stone

William L. Stone
Laboratory Manager

P.O. Box 12015, Research Triangle Park, North Carolina 27709• (919) 544-1735• Fax (919) 544-0810• 1-800-327-5832• www.ecslimited.com
Aberdeen, MD · Atlanta, GA · Austin, TX · Baltimore, MD · Chantilly, VA · Charlotte, NC · Chicago, IL · Danville, VA* · Frederick, MD · Fredericksburg, VA · Greensboro, NC
Greenville, SC · Norfolk, VA · Research Triangle Park, NC · Richmond, VA · Roanoke, VA · Williamsburg, VA · Wilmington, NC* · Winchester, VA*
*Testing Services Only

ARCADIS GERAGHTY & MILLER

Laboratory Task Order No./P.O. No. ______

CHAIN-OF-CUSTODY RECORD

Page 1 of 1

Project Number/Name RN009900.0003.MA003

Project Location Hanscom AFB

Laboratory ______

Project Manager Chris Lutes (919-544-4535)

Sampler(s)/Affiliation JB/SD - ARCADIS

Sample ID/Location	Matrix	Date/~~Time~~ Sampled	Time ~~Lab ID~~	ANALYSIS / METHOD / SIZE Grain Size						Remarks	Total
IRZ-4(44-46)	S	5/11/00	9:50	1							1
IRZ-INJ	S	5/12/00	—	1							1
IRZ-2 (39-41)	S	5/13/00	1540	1							1
IRZ-3(44-46)	S	5/8/00	1100	1							1
HAN-SS-IRZ-1(44-45)	S	5/16/00	12:00	1							1

Sample Matrix: L = Liquid; S = Solid; A = Air

Total No. of Bottles/Containers 5

Relinquished by:	Organization: ARCADIS	Date 5/16/00	Time 2:00P	Seal Intact?
Received by:	Organization: ECS, Ltd.	Date 5/17/00	Time 11:25Am	[✓ Yes] No N/A
Relinquished by:	Organization:	Date / /	Time	Seal Intact?
Received by:	Organization:	Date / /	Time	Yes No N/A

Special Instructions/Remarks: ______

Delivery Method: ☐ In Person ☒ Common Carrier Fed Ex (SPECIFY) ☐ Lab Courier ☐ Other ______ (SPECIFY)

AG 05-0597

Engineering Consulting Services, Ltd.
P.O. Box 12015
RTP, NC 27709
(800) 327-5832
(919) 544-1735 Fax

Grain Size Analysis

Job Name **Arcadis, Geraghty & Miller**
Job No. **7597-A**

Boring No. **IRZ-INJ**
Sample No. **IRZ-INJ**
Sample Depth (ft.) Not Available
Sample Description Gray silty gravel with sand
U. S. C. S. Classification: GM

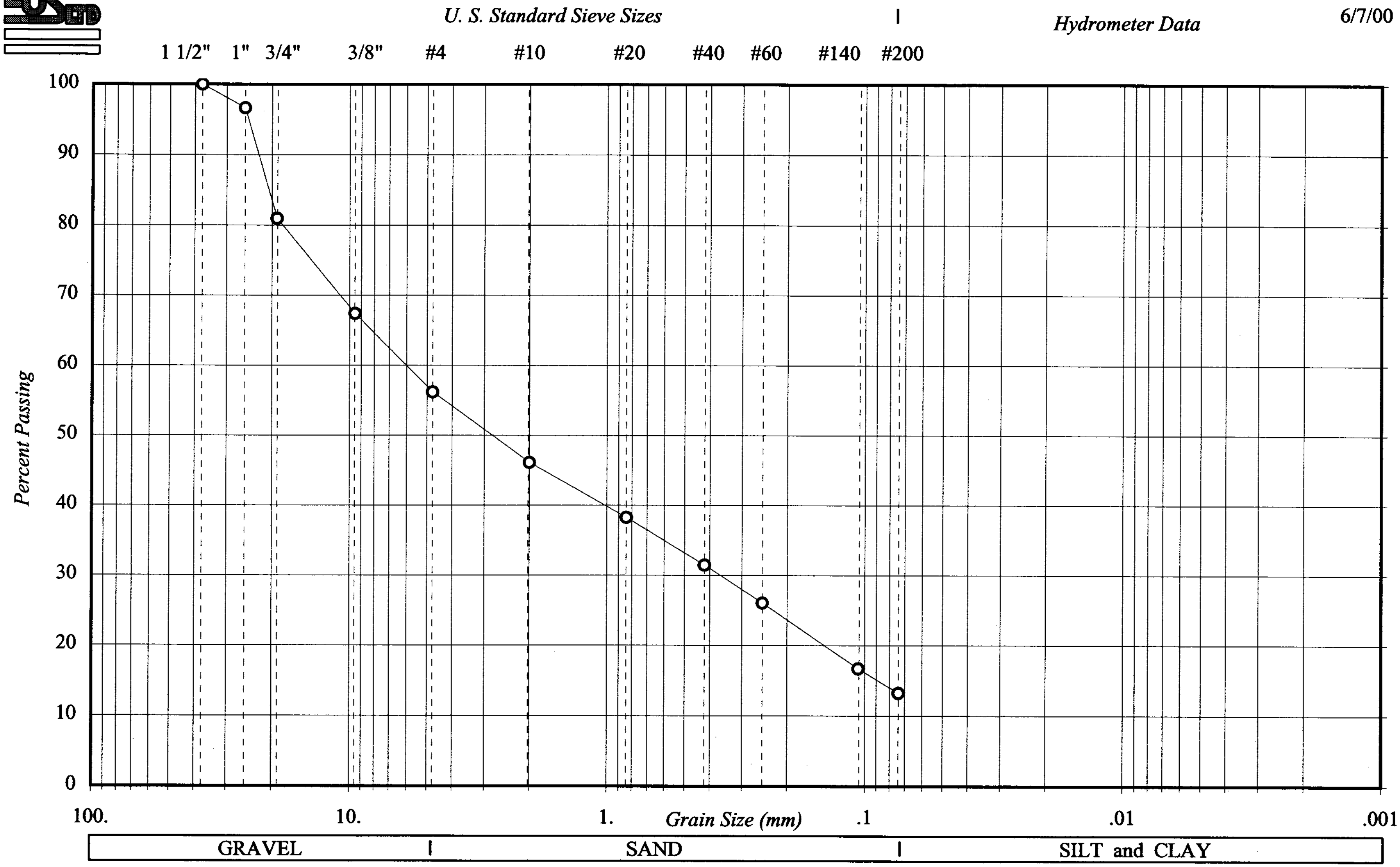
Dry Weight of Sample 788.39 g

Sieve Number	**Diameter [mm]**	**Percent Passing**	**Percent Retained**
1 1/2"	37.5	100.0	0.0
1"	25.4	96.7	3.3
3/4"	19.10	81.0	19.0
3/8"	9.52	67.4	32.6
#4	4.76	56.2	43.8
#10	2.00	46.1	53.9
#20	0.84	38.2	61.8
#40	0.42	31.4	68.6
#60	0.25	26.0	74.0
#140	0.106	16.7	83.3
#200	0.074	13.2	86.8

Grain Size Analysis

ECS Job No.: 7597-A

6/7/00



Sample description: Gray silty gravel with sand

Cu = Indeterminant

U. S. C. S. Classification: GM

Cc = Indeterminant

Job Name: **Arcadis, Geraghty & Miller**
Sample No.: **IRZ-INJ**
Sample Depth: Not Available

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(919) 544-1735 Fax

Grain Size Analysis

Job Name **Arcadis, Geraghty & Miller**
Job No. **7597-A**

Boring No. **HAN-SS-IRZ-1**
Sample No. **HAN-SS-IRZ-1 (44-45) I**
Sample Depth (ft.) 44 - 45
Sample Description Gray silty sand with gravel
U. S. C. S. Classification: SM

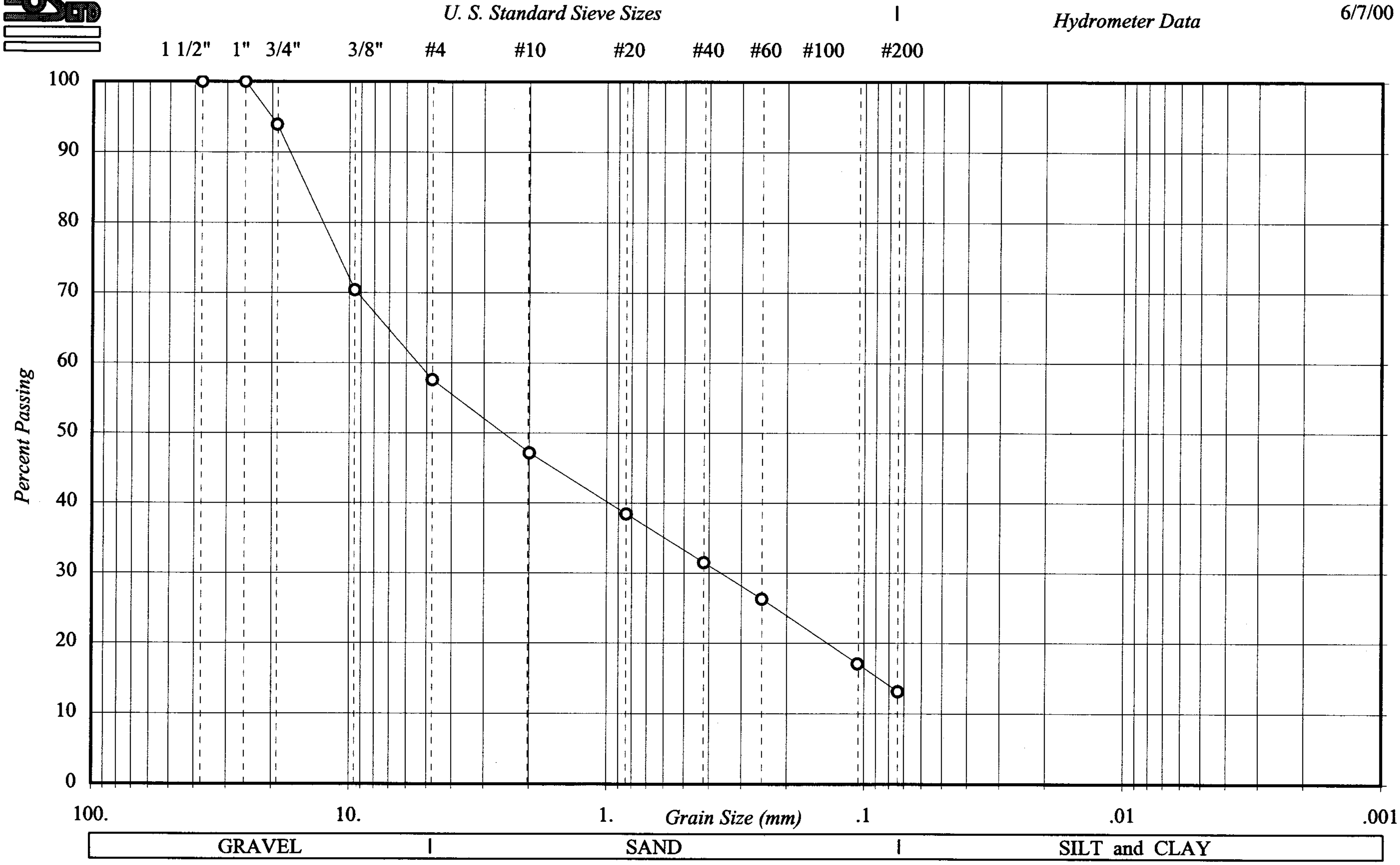
Dry Weight of Sample 406.55 g

Sieve Number	Diameter [mm]	Percent Passing	Percent Retained
1 1/2"	37.5	100.0	0.0
1"	25.4	100.0	0.0
3/4"	19.10	93.9	6.1
3/8"	9.52	70.4	29.6
#4	4.76	57.6	42.4
#10	2.00	47.1	52.9
#20	0.84	38.4	61.6
#40	0.42	31.5	68.5
#60	0.25	26.3	73.7
#140	0.106	17.1	82.9
#200	0.074	13.2	86.8

Grain Size Analysis

ECS Job No.: 7597-A

6/7/00



Sample description: Gray silty sand with gravel

Cu = Indeterminant

Cc = Indeterminant

U. S. C. S. Classification: SM

Job Name: **Arcadis, Geraghty & Miller**

Sample No.: **HAN-SS-IRZ-1 (44-45) I**

Sample Depth 44 - 45

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(919) 544-1735 Fax

Grain Size Analysis

Job Name **Arcadis, Geraghty & Miller**
Job No. **7597-A**

Boring No. **HAN-SS-IRZ-1**
Sample No. **HAN-SS-IRZ-1 (44-45) II**
Sample Depth (ft.) 44 - 45
Sample Description Gray poorly graded gravel with silt and sand
U. S. C. S. Classification: GP-GM

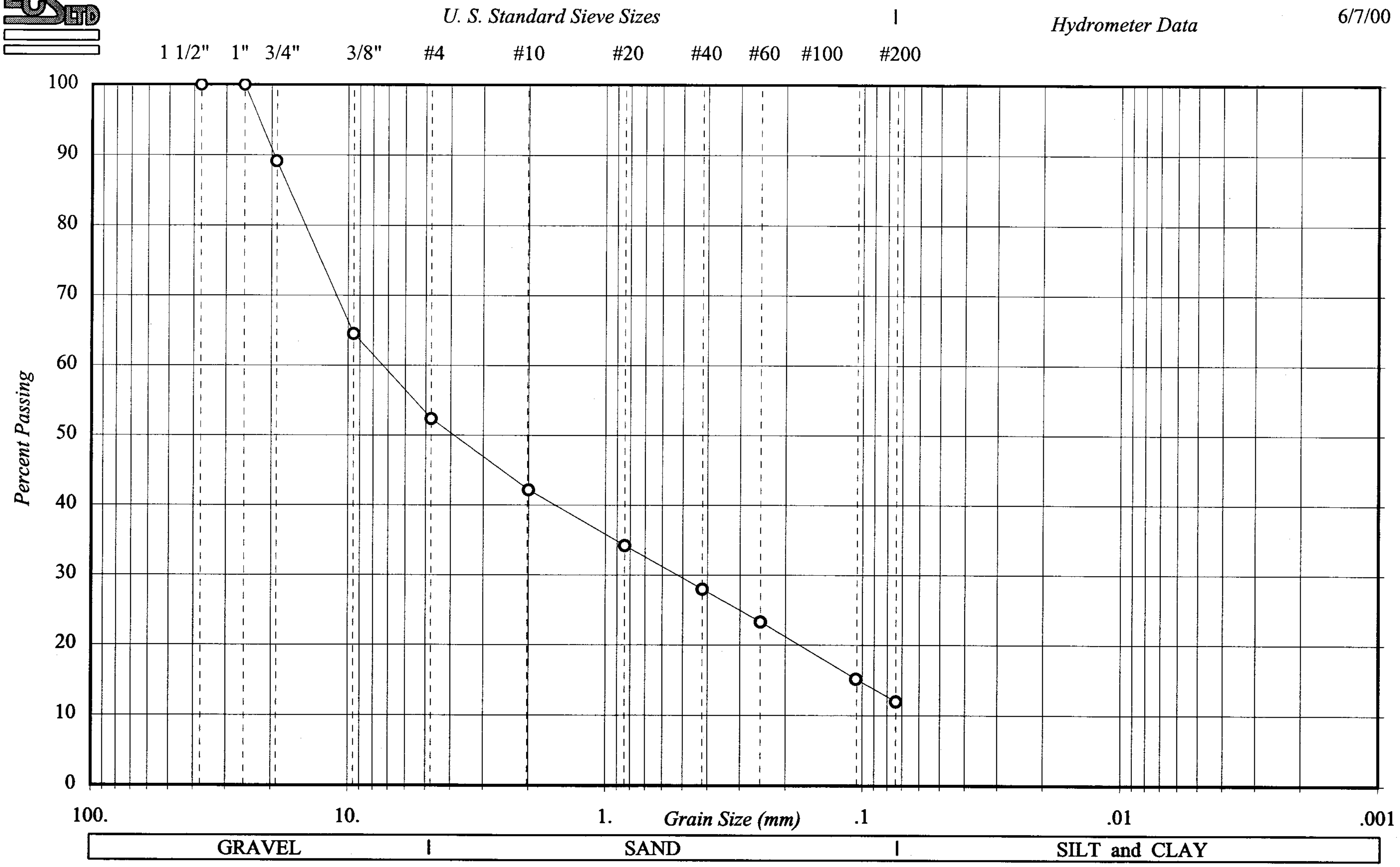
Dry Weight of Sample 344.22 g

Sieve Number	Diameter [mm]	Percent Passing	Percent Retained
1 1/2"	37.5	100.0	0.0
1"	25.4	100.0	0.0
3/4"	19.10	89.1	10.9
3/8"	9.52	64.5	35.5
#4	4.76	52.4	47.6
#10	2.00	42.2	57.8
#20	0.84	34.2	65.8
#40	0.42	27.9	72.1
#60	0.25	23.3	76.7
#140	0.106	15.2	84.8
#200	0.074	12.0	88.0

Grain Size Analysis

ECS Job No.: 7597-A

6/7/00



Sample description: Gray poorly graded gravel with silt and sand

Est. Cu 0.4

U. S. C. S. Classification: GP-GM

Est. Cc = 0.7

Job Name: **Arcadis, Geraghty & Miller**

Sample No.: **HAN-SS-IRZ-1 (44-45) II**

Sample Depth (ft.): 44 - 45

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Grain Size Analysis

Job Name **Arcadis, Geraghty & Miller**
Job No. **7597-A**

Boring No. **IRZ-2**
Sample No. **IRZ-2 (39-41)**
Sample Depth (ft.) 39-41
Sample Description Gray silty sand with gravel
U. S. C. S. Classification: SM

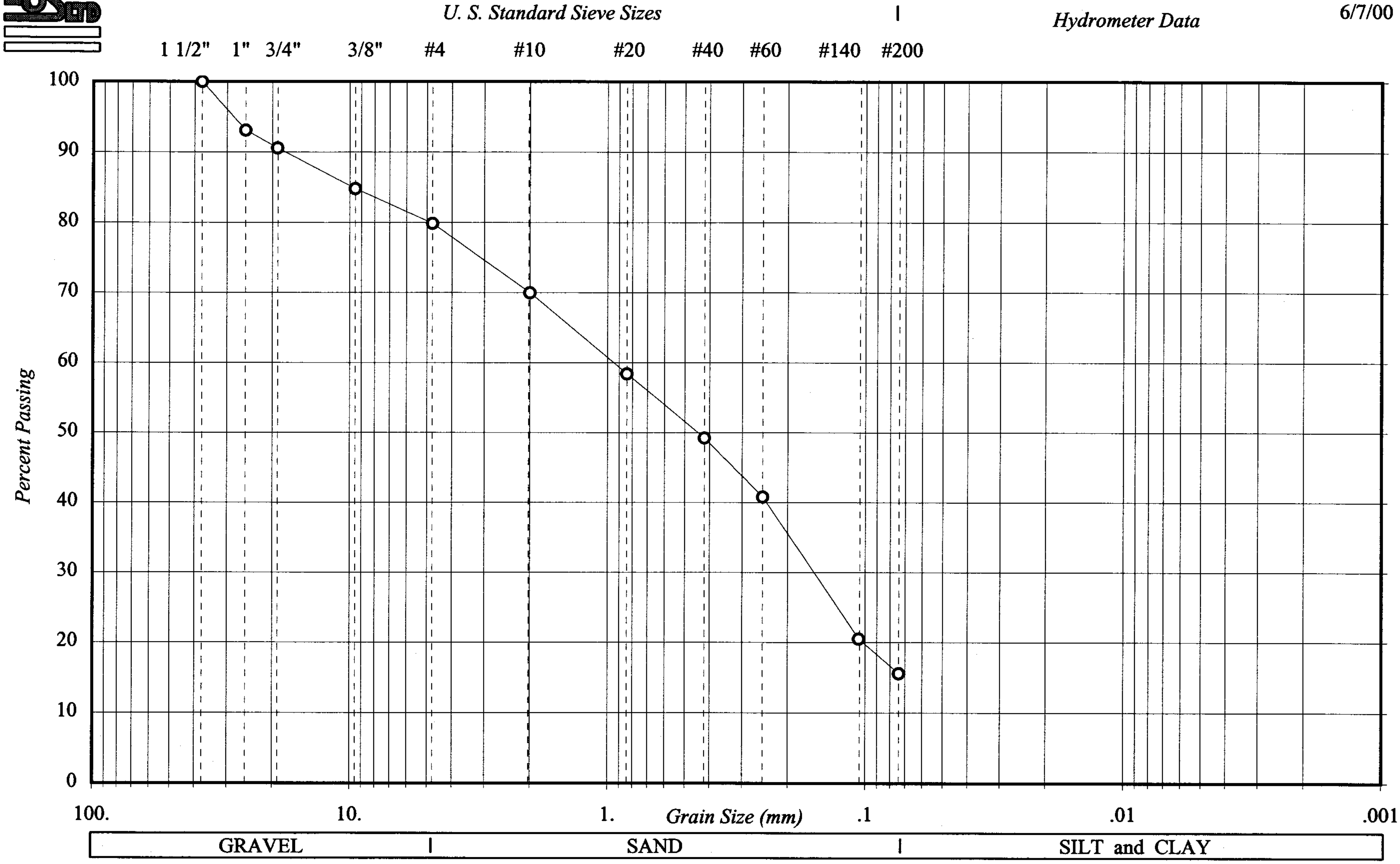
Dry Weight of Sample 777.12 g

Sieve Number	Diameter [mm]	Percent Passing	Percent Retained
1 1/2"	37.5	100.00	0.00
1"	25.4	93.09	6.91
3/4"	19.10	90.58	9.42
3/8"	9.52	84.78	15.22
#4	4.76	79.83	20.17
#10	2.00	69.98	30.02
#20	0.84	58.41	41.59
#40	0.42	49.20	50.80
#60	0.25	40.78	59.22
#140	0.106	20.52	79.48
#200	0.074	15.58	84.42

Grain Size Analysis

ECS Job No.: 7597-A

6/7/00



Sample description: Gray silty sand with gravel

Cu = Indeterminant

U. S. C. S. Classification: SM

Cc = Indeterminant

Job Name: **Arcadis, Geraghty & Miller**

Sample No.: **IRZ-2 (39-41)**

Sample Depth: 39-41

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Grain Size Analysis

Job Name **Arcadis, Geraghty & Miller**
Job No. **7597-A**

Boring No. **IRZ-3**
Sample No. **IRZ-3 (44-46)**
Sample Depth (ft.) 44 - 46
Sample Description Gray silty sand with gravel
U. S. C. S. Classification: SM

Dry Weight of Sample 785.74 g

Sieve Number	Diameter [mm]	Percent Passing	Percent Retained
1 1/2"	37.5	100.00	0.00
1"	25.4	93.22	6.78
3/4"	19.10	85.52	14.48
3/8"	9.52	72.21	27.79
#4	4.76	62.01	37.99
#10	2.00	51.38	48.62
#20	0.84	42.84	57.16
#40	0.42	35.68	64.32
#60	0.25	29.84	70.16
#140	0.106	18.23	81.77
#200	0.074	14.16	85.84

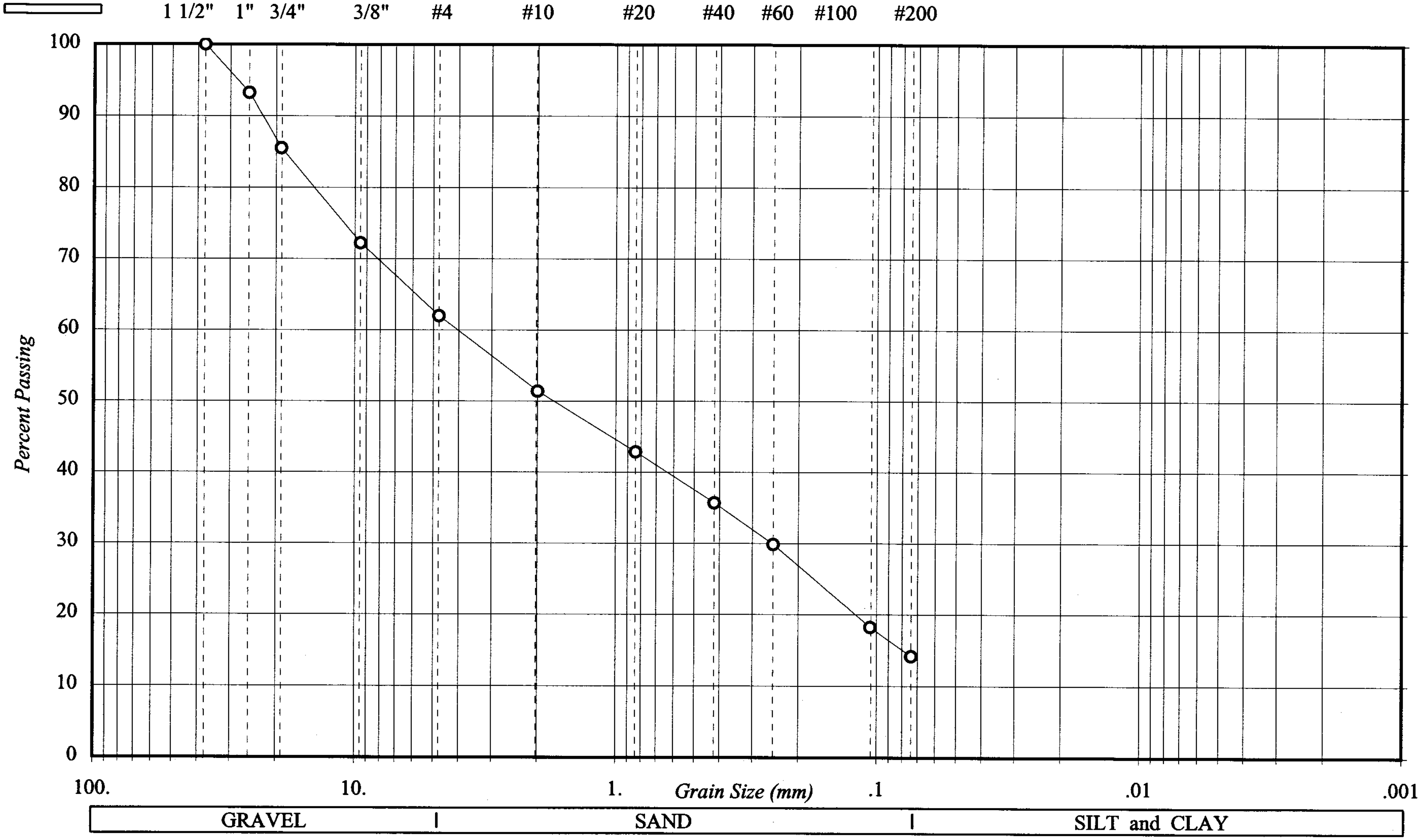
Grain Size Analysis

ECS Job No.: 7597-A

6/7/00

U. S. Standard Sieve Sizes

Hydrometer Data



Sample description: Gray silty sand with gravel

Cu = Indeterminant

U. S. C. S. Classification: SM

Cc = Indeterminant

Job Name: **Arcadis, Geraghty & Miller**
Sample No.: **IRZ-3 (44-46)**
Sample Depth: 44 - 46

Engineering Consulting Services, Ltd.
P.O. Box 12015
RTP, NC 27709
(800) 327-5832
(919) 544-1735 Fax

Grain Size Analysis

Job Name **Arcadis, Geraghty & Miller**
Job No. **7597-A**

Boring No. **IRZ-4**
Sample No. **IRZ-4 (44-46)**
Sample Depth (ft.) 44 - 46
Sample Description Gray silty sand with gravel
U. S. C. S. Classification: SM

Dry Weight of Sample 725.56 g

Sieve Number	**Diameter [mm]**	**Percent Passing**	**Percent Retained**
1 1/2"	37.5	100.00	0.00
1"	25.4	100.00	0.00
3/4"	19.10	93.30	6.70
3/8"	9.52	75.93	24.07
#4	4.76	65.26	34.74
#10	2.00	54.75	45.25
#20	0.84	45.66	54.34
#40	0.42	39.38	60.62
#60	0.25	29.28	70.72
#140	0.106	20.02	79.98
#200	0.074	15.81	84.19

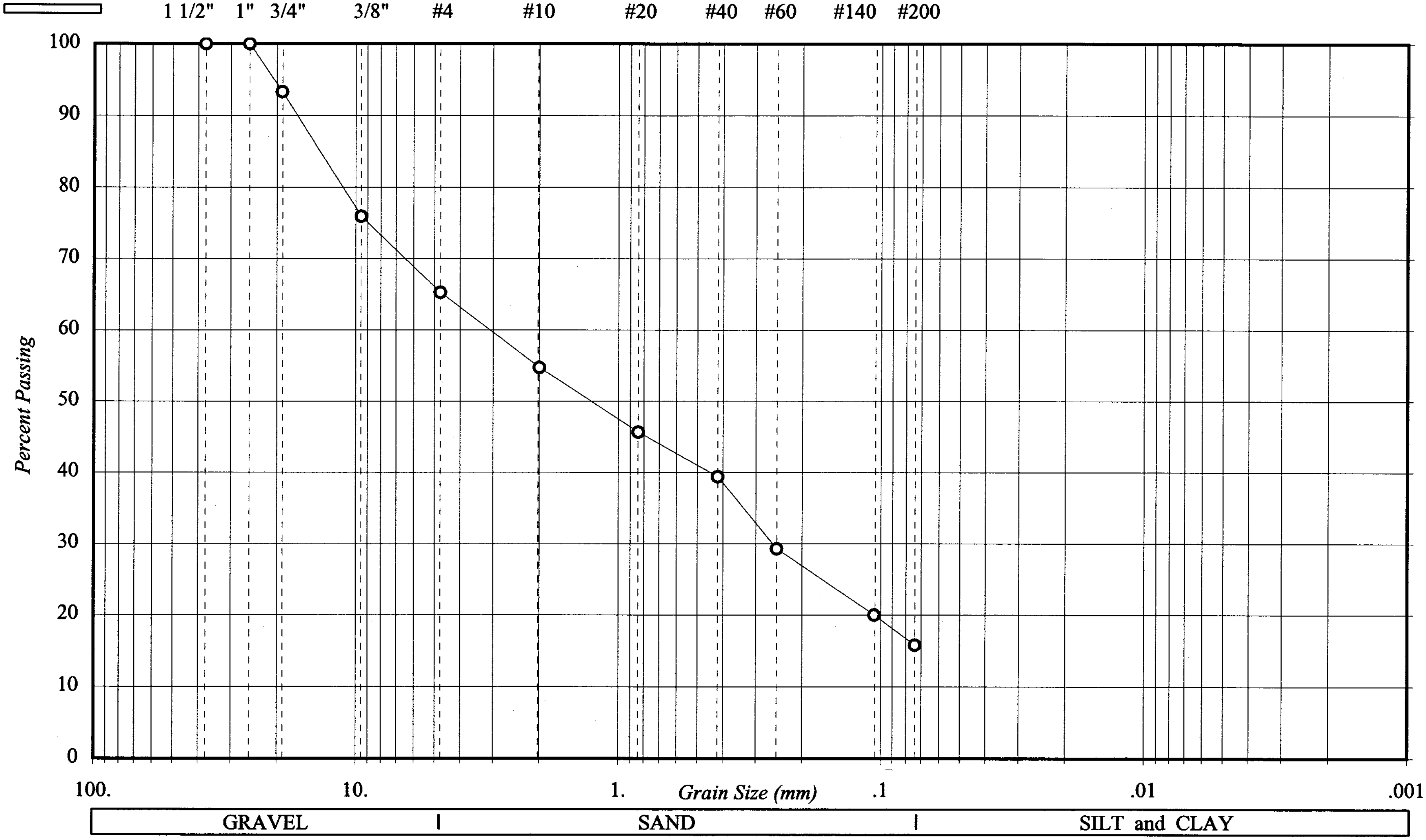
Grain Size Analysis

ECS Job No.: 7597-A

6/7/00

U. S. Standard Sieve Sizes

Hydrometer Data



Sample description: Gray silty sand with gravel

Cu = Indeterminant

U. S. C. S. Classification: SM

Cc = Indeterminant

Job Name: **Arcadis, Geraghty & Miller**

Sample No.: **IRZ-4 (44-46)**

Sample Depth: 44 - 46

Appendix A-3

Standard Operating Procedure: Field Screening of Water & Vapor Samples for Volatile Organic Compounds by Gas Chromatography

Standard Operating Procedure
Field Screening of Water & Vapor Samples for Volatile Organic Compounds by Gas Chromatography

---

1.0 Scope and Application

This gas chromatograph/photoionization detector (GC/PID) method is applicable to the detection of trichloroethylene (TCE) and cis-1,2-dichloroethene (cis-DCE) in water and vapor samples at the Hanscom AFB project site.

2.0 Summary

Samples are analyzed on site using a portable GC/PID, using direct injection of vapor samples from off-gas treatment systems or injection of the headspace of water samples. The identification of target analytes is determined by retention time comparison to standard materials. The concentration of target analytes is calculated using the external standard technique.

3.0 Interferences and Limitations

This method is useful for providing reliable screening data quickly and cost effectively, and should not be considered definitive data. As with any GC method, any compounds co-eluting with cis-DCE or TCE can produce an erroneously high concentration or a misidentification of the target analyte.

4.0 Sample Collection

Standard volatile sample collection procedures should be followed for collecting a representative sample. Water samples should be collected in 40 ml VOA vials, with no observable headspace.

5.0 Sample Preservation

5.1 Water samples should be stored at 4°C until analyzed. Unpreserved samples will be analyzed within 7 days of collection and acid preserved samples will be analyzed within 14 days.

5.2 No preservation of vapor samples is required. Vapor samples will be analyzed within eight hours of collection if using Tedlar Bags. The holding time using the Microseeps technique is 14 days.

6.0 Apparatus

6.1 Photovac Model 10s50 portable GC with PID, strip chart recorder, and electronic integrator.

6.2 Capillary column – 1 meter CPSIL 5 pre-column with a 9 meter CPSIL analytical column.

6.3 Photovac low power isothermal oven powered by a globe/cell rechargeable battery pack.

6.4 Dilution, standard preparation, and sample injection syringes (with syringe cleaner) in varying sizes allowing for accurate injection volumes from 10 to 1000 μL. Syringes used for injection of sample into the GC should be gas tight.

6.5 Dual flow meter (range 0 to 55cc/mL).

6.6 Zero grade air will be used as the carrier gas.

6.7 Tedlar Bags and 40 mL VOA vials.

6.8 Calibration gas mixture for vapor analysis.

6.9 Liquid standards, methanol and distilled water for preparation of water standards.

7.0 GC/PID Operating Parameters

7.1 Set gain at 10

7.2 Set isothermal oven at 30°C

7.3 Set flow at 6 mL

7.4 Set backflush at 30 seconds

7.5 Set runtime at 360 seconds

8.0 Standard Preparation

8.1 All standard preparation shall be documented in the Standard Preparation Logbook. At minimum, the following will be recorded for each standard solution; Date, initials, source of standard, composition of standard, and lot #'s for reference solutions.

8.2 All standards must be labelled with the standard name and date prepared, such that it can be traced back to the Standard Preparation Logbook.

8.3 Gas Standard

8.3.1 A specialty gas mixture cylinder with a certified concentration of 1 ppm (v/v) of cis-1,2-DCE and TCE will be purchased for standardizing the GC for vapor samples.

8.3.2 The cylinder will be used to create a working standard by filling a Tedlar bag dedicated to the standard. This working standard will be valid for eight hours.

8.4 Liquid Stock Standard

8.4.1 Certified reference mixtures of individual standards for cis-1,2-DCE and TCE at a concentration of 5,000 µg/ml in methanol will be purchased for the preparation of the working water standards.

8.4.2 The reference standards should be tightly sealed and stored in the refrigerator and allowed to warm to room temperature before use.

8.4.3 Observe the meniscus of a previously used standard to ensure that the vial has remained tightly sealed during storage. If the meniscus does not match the marking on the vial from its previous use, the standard must be discarded and a new reference mix should be used.

8.4.4 After the reference has been used, mark the meniscus of remaining standard before returning the standard to the refrigerator for storage.

8.5 Liquid Working Standard

8.5.1 The working standard, at a concentration of 1,700 µg/ml of each target analyte is prepared by combining 300 µl of each reference standard and 420 µl of reagent grade methanol.

8.5.2 The working standard should be prepared in a screw top vial equipped with a Mininert valve to reduce evaporation during use, and must be refrigerated between uses.

8.5.3 A new working standard will be prepared when calibration standards indicate degradation of the standard or a significant change in standard concentration due to evaporation. See Section 11.0.

8.6 Liquid Calibration Standard

8.6.1 Add 34 ml of distilled water to a 40 mL VOA (40mL is the nominal volume, but the actual capacity is 44 mL). This will leave a headspace volume of 10 mL.

8.6.2 Allow the working standard to warm up to room temperature.

8.6.3 Open the Mininert valve, insert a 10 µl syringe, and fill the syringe with 10 µl of the standard.

8.6.4 Inject the working standard into the water in the vial prepared in step 8.6.1.

8.6.5 This calibration standard, equivalent to 0.5 ppm, or 500 ppb, will be used to calibrate the GC.

8.6.6 The calibration standard must be used within eight hours.

8.6.7 Additional concentration standards can be prepared by adjusting the volume of working standard added to the 40 mL vial.

9.0 Sample Preparation

9.1 Samples will be allowed to set undisturbed at room conditions in order to reach thermal equilibrium prior to analysis. (A minimum of 30 minutes for vapor samples and 60 minutes for liquid samples.)

9.2 10 mL of water will be removed from the vial to create a headspace prior to analysis. Insert a syringe needle through the vial septa then use another syringe to withdraw and discard 10 mL of sample. Water samples will then be shaken vigorously for 20 seconds prior to extracting the headspace for analysis.

10.0 Initial Calibration

10.1 A three-point calibration curve will be conducted to establish the linear range of the instrument. A zero grade air blank will be analyzed before and following the three standards.

10.2 Three different volumes of the specialty gas standard will be used to generate the curve for vapor analysis.

10.3 Three different concentrations water standards will be prepared by injecting three different volumes of the working standard into vials filled with 34 mL of water.

10.4 The linear regression for the three points will be calculated. The curve will be acceptable if the correlation coefficient for the curve is greater than or equal to 0.98.

11.0 Daily Calibration

11.1 Daily calibration shall be performed using a working standard within the calibration range established with the three-point curve. A blank will be analyzed before and after the standard.

11.2 The response factor will be calculated by:

$R_f = (A/B)/C$

Where:

A = Total instrument response (sum of the area under the peak in the retention time window).
B = Injection volume (µl) of the standard
C = concentration of standard

11.3 If the daily response factor is >150% the mean response factor for the initial calibration curve, then the appropriate check and corrective action will be taken (i.e. reinjection of standard, re-make standard, clean detector etc…).

12.0 Sample Analysis

12.1 Samples will be injected into the instrument in the same manner as standards. Injection volumes may vary based on sample concentration.

12.2 If no peaks of interest are observed or the peak heights are below the calibration range, then reanalysis may be performed at a higher injection volume (up to 1000µl).

12.3 If a sample peak exceeds the linear range established with the three point calibration curve, then reanalysis may be performed using smaller injections (down to 10 µl). A dilution may be conducted if the instrument response still exceeds the linear range.

12.4 The concentration of a compound can be determined either manually using Rf's or by setting up the Photovac's integrator.

12.4.1 Concentrations by Rf's are calculated by the formula:

$C = A/(R_f \times B)$
C = Concentration of compound ppm

A = VS of the peak as printed out by the integrator
R_f = Daily response factor (Reference Section 10.2)
B = Injection volume (μl)

12.4.2 Following the calibration of the 10s50, enter the required data into the integrator memory per the instruments operation manual. Correct for variation in injection volume.
C = A/(B/D)
C = Actual concentration of the compound in ppm
A = Concentration in ppm calculated and printed out by the 10s50 integrator
B = Injection used for standard that the integrator was set up on
D = injection volume of sample

13.0 Quality Control

13.1 Instrument blanks will be run at the start of each day.

13.2 A zero grade air blank (syringe blank) will be analyzed at the start and end of each day, after every 20 samples and after grossly contaminated samples.

13.3 A duplicate sample will be analyzed at a frequency of once per 50 samples analyzed.

13.4 Calibration standards will be analyzed at the start and end of each day and at a minimum frequency of once per every 20 samples.

13.5 A calibration standard will be analyzed whenever system maintenance (such as septa change, carrier gas recharge) is performed.

14.0 Method Detection Limit

14.1 The method detection limit (MDL) will be calculated at least once per year.

14.2 Prepare a calibration standard at three to five times the estimated MDL.

14.3 Analyze this standard seven times.

14.4 Calculate the standard deviation of the seven results.

14.5 The MDL is 3.14 times the calculated standard deviation.

Appendix A-4a

Boring Logs and Well Construction Diagrams

ARCADIS GERAGHTY & MILLER

DAILY LOG

Well(s) IRZ-2 Project/No. RN009900.0003 MA003 Page ____

Site Location Hanscom AFB

Prepared By S Darrigrand

Date/Time	Description of Activities
5/3/00	~~50~~ sunny 60s
820	arrived onsite spoke with Dan of IT group
	showed me where well locations are
910	drillers arrived - Mike & Todd
930	set up on IRZ-2 - SE of drainage ditch
940	staging equipment
1030	began drilling
1050	Saravanan onsite with sample containers
	left containers @ plant with Dan
1115	Saravanan offsite
1120	drillers hit water at 10' have to stop to fill
	water tank & run water cap
1210	drillers returned
1330	drillers down to 20' sand is grey Mike is
	concerned that sand will cement augers
1440	drillers to 30' Mike says it appears to be
	top of till
1520	sampled from 39'-41' - called Saravanan - told him we were into till
1600	drilled to 45' drillers only have 10' of screen
	called Saravanan - he said that would be acceptable
	for this hole only - told us to set well
1615	set well to 43.5' - screened to 33.5' sand to 31' bent to 28
1700	left site

ARCADIS GERAGHTY & MILLER

DAILY LOG

Well(s)________ Project/No. RN009900.0003.MA003 Page ____

Site Location AFCEE

Prepared By S Darligrand

Date/Time	Description of Activities
5/4/00	sunny 60 Tom 781-377-4455
745	arrived onsite - drillers here
	Scope grout & finish IRZ-2 and move to
	IRZ-1
830	Tom Best onsite - discussed access to
	runway and locations of wells - did not like
	location of IRZ-3
915	Tom offsite - drillers drumming soil and cleaning
	augers
1025	set up on IRZ-1 and began drilling
1100	Rich from IT group onsite discussed use of HNU
1115	Rich offsite - hole @ 12'
1200	hole @ 20' sand surged around water cap
1215	pulled augers because they are clogged
	with sand
1250	drillers back in hole - down to 8'
1350	Tom & Saravanan onsite to measure well
	locations
1430	down to 34' - sand surging up augers - talked
	to Saravanan told him augering not working - drillers
	suggested driving and washing - Tom discussed relocating
	hole - drillers pulled augers

ARCADIS GERAGHTY & MILLER

DAILY LOG

Well(s) ______ Project/No. RN009900.0003.MA003 Page ___

Site Location Hanscom AFCEE

Prepared By S Darligrand

Date/Time	Description of Activities
5/5/00	
740	arrived onsite-drillers filling water tank
800	set roadbox on IRZ-2
820	Rich from IT group said airport could not be closed today
830	set up rig on new IRZ-3 location
845	drillers fitting 6" casing thread and setting up
950	drilling begins
1120	break for lunch - down to 15'
1150	resumed work
1430	down to 40' stopped to clean up
1530	left site

ARCADIS GERAGHTY & MILLER

DAILY LOG

Well(s) ______ Project/No. RN009900.0003.MA003 Page ____

Site Location AFCEE

Prepared By S Darrigrand

Date/Time	Description of Activities
5/8/00	sunny 75°
745	arrived onsite
	Scope: finish TRZ-3 and set well
830	drilling down to 43' beginning to encounter
	very dense material possibly top of bedrock
	plan to collect spoon sample from 44'-46'
1030	tried a sample [illegible]
	sample no [illegible] tried another from 4[illegible]
1315	talked to [illegible] updated him on status of
1320	drilling to 54' [illegible] retract - dropped
	sample [illegible]
1530	reached bedrock at [illegible] [illegible]
	said we should set well
1530	broke apart 4" casing
1800	left site

ARCADIS GERAGHTY & MILLER

DAILY LOG

Well(s) ______ Project/No. RY000999.0003.MA003 Page ____

Site Location ASCEE

Prepared By S Brigand

Date/Time	Description of Activities
5/9/99	[illegible] 80
800	arrived onsite drillers setting up [illegible]
	well set at 54' - screened to 39' - sand to 37'
845	spoke with Tom B - wants to make injection
	well [illegible]
1015	drillers grouting in well
1115	[illegible]
1140	drillers decontaminating equipment
1300	setting up to drill [illegible]
1330	[illegible]
1530	down to 24' grey silty clay
1630	down to 29' - packed up - left site
	5695
24	
	it 13
	4.5
	Adams

ARCADIS GERAGHTY & MILLER

DAILY LOG

Well(s)______ Project/No. RN009900.0003.MA003 Page ___

Site Location AFCEE

Prepared By S. Darsigny

Date/Time	Description of Activities
5/10/00	
745	arrived onsite
800	drillers onsite
815	drilling began
940	at 36.5' encountered rock
1000	bit not able to penetrate rock
	spoke with Tom B[illegible] no [illegible] of bedrock
	in the area as high as 35'
1005	spoke with Chris L-updated him ~~on~~ situation
	told him that we would not be able to pass
	6" casing through pilot hole
	drillers suggested different bit on 4" casing
	to pass through boulder and set 2" well
	Chris said to go ahead with 2" well
1030	New plan - ~~they~~ suspect rock @36' is a large
	boulder, not bedrock - drill through boulder with
	smaller bit and set 2" well
1200	down to 39' driller thinks it may be bottom of
	boulder
1237	screened sample of soil from tub - only background
	readings
1340	lightning - shutdown resumed at 1500
[illegible]	[illegible] boulder at 39' left site

ARCADIS GERAGHTY & MILLER

DAILY LOG

Well(s) ______ Project/No. RN009960.0003.MA003 Page ____

Site Location IFCEE

Prepared By S Dorigrand

Date/Time	Description of Activities
5/11/00	Cloudy, 50
800	arrived onsite
	Scope sample till below boulder in IRZ-4
	set well
830	flushed material out of hole & resetting 4"
	casing within 5" casing
915	attempted to sample [illegible] : no recovery
	still in boulder material
950	sampled 44-45' - PID reading of ≈65 ppm
1120	down to bedrock at 51.2'
1130	broke for lunch
1200	resumed with setting well and pulling casing
	well @ 51' ~~set~~ screened to 35'
1330	prepping for installation of injection well
1600	casing deconned - ready for installation
	on other side of fence
	left site

ARCADIS GERAGHTY & MILLER

DAILY LOG

Well(s)_______ Project/No. RN009900.0003 Page ____

Site Location AFCEF

Prepared By S Dalrigrand

Date/Time	Description of Activities
5/12/00	
740	arrived onsite
	coordinated with Rich from IT for airport
	clearance and power down of 13Kv line
750	moved out onto field
825	began drilling
1150	down to [illegible] broke for lunch
1500	collected sample 44-45'
[illegible]	left area to work on system
1615	Put valve on condensation line
1620	lines from wells are 1¼" piping
	check valves are 1" - did not install

ARCADIS GERAGHTY & MILLER

DAILY LOG

Well(s) Injection well Project/No. RNCE9900.0003 Page ___

Site Location AFCEF

Prepared By J. Bonsteel

Date/Time	Description of Activities
5/15/00	
9:30A	Arrive in Lexington. Call Sam, who meets me and
	brings me to site. Meet drillers (Mike + Mike),
	Rich from IT Group. Go over work w/Sam,
	sampling requirements, etc.
10:45	Sam departs site. Well @ depth (51.2' bls)
	Installing well casing.
11:15	Well screen 36-55', sand to 34', bentonite to 32',
	grout to surface
	Call Tom Best to introduce myself + give him my
	cell number and update on job progress.
11:40	After taking DTB measurements, Mike determines
	well bottom @ 49', sand to 30' (overshot by 2').
	Talk w/Sam and have drillers try to wash out 2'
	of sand. Attempt + unable, due to well casing
	(can't get hose down)
12:20	Finish grouting injection well
13:10	Move rig + set-up on IRZ-1
13:40	Begin IRZ-1
14:15	30' casing in ground. Tom Best stops out and
	says we can leave rig (boom down) on hole overnight.
15:45	Drive 35' casing into ground.
16:30	Drive 40' casing into ground

ARCADIS GERAGHTY & MILLER

DAILY LOG

Well(s)________ Project/No. RN0009900.0003 Page 1

Site Location HANSCOM AFB

Prepared By J. Bonsteel

Date/Time	Description of Activities
5/16/00	
7:00A	Arrive on-site. Set-up sample bottles. Get FFD/PFD. Have difficulty figuring out contents. Will call Sam to confirm sample bottle quantity + FFD/PFD, etc.
7:45	Geologic arrive. Awaiting clearance to get on AFB.
8:30	Access granted. Drive to IRZ-1 location
9:20	Drive 35-40' casing.
10:00	Pulled off site by MASSPORT due to emergency landing.
10.30	Told emergency landing would occur in 2-3 hrs due to fuel supply of plane. Asked for permission to continue work until requested to leave again - permission denied. Will have to wait until landing until restart work. On stand-by.
11:15	Notified the plane will make landing at different airport. Cleared to continue work
11.45	Attempt 44-46' spoon - very dense; stop blows after getting to 45'
12:00	Collect MAN-35-IRZ-1 (44-45')

ARCADIS GERAGHTY & MILLER

DAILY LOG

919-544-4535
Chris Lutes

Well(s) FRZ-1 Project/No. RN009900.0003.MA003 Page 2

Site Location Bedford (Hanscom AFB)

Prepared By J. Barsteel

Date/Time 5/16/00	Description of Activities
12:50	Boulders encountered @ depth. Unable to drive
	casing further. Call Rich (Lowell) and confirm
	it is OK to set well in open borehole
	@ 48.5' (Bedrock).
13:05	Talk w/ Sam + go over progress.
13:55	Well bottom @ 48.4'
	Screen 48.4' to 33.4'
	Sand to 30.5'
	Bentonite to 28.5'
15:05	Grout to grade
	Talk w/ Chris Lutes (NC) about well details + lab
	for grain size analysis
	Talk w/ Chuck (Lowell) about development water storage/
	disposal. Will speak w/ Sam to see if he knows
	what agreement was reached w/ Tom Best.
16:00	Finish FRZ-1. Packing up rig + equipment
16:45	Drop off samples @ Fed Ex.

FRZ-1
Well Construction

ARCADIS GERAGHTY & MILLER

DAILY LOG

Well(s)______ Project/No. RN009900.0003.MA003 Page 1

Site Location Hanscom AFB

Prepared By J. Bonsteel

Date/Time	Description of Activities
5/17/00	
7:00A	Arrive onsite
9:00A	Geologic arrives onsite. Unload empty drums. Call Tom Best (leave message) to see if we can bring rig (boom up) onto property.
9:30	Set up on IRZ-INJ to develop w/ "whaler" pump
	IRZ-2 to IRZ-3 ~30'
	6T to IRZ-4 ~21'
	6T to IRZ-INJ ~35'
	6S to IRZ-1 ~16'
10:30	Developing IRZ-INJ w/ "whacker" pump + foot valve
12:00	Pump on 1.5 hrs. → 275g still silty turbid
	1v = 28g
	10v = 280g
1:10P	IRZ-INJ developed for 3 hrs. 525g removed
	Turbidity → slightly turbid/silty (better than start)
1:30P	Set up on IRZ-1 and start development.
2:30P	200g out of IRZ-1, clearing up, will pump 250g then stop
3:15P	250 g removed IRZ-1 clear

ARCADIS GERAGHTY & MILLER

DAILY LOG

Well(s)________ Project/No. RN009900.0003.MA003 Page 1

Site Location Hanscom AFB

Prepared By J. Bonsteel

Date/Time	Description of Activities
5/18/00	
7:00A	Arrive onsite. Geologic arrives onsite
8:15A	Moving soil drums.
8:50	Set-up for development of IRZ-4
9:10A	Start IRZ-4 Development (whaler pump + Foot valve)
	1v = 7g 3v = 21g 10v = 70g
10:55A	IRZ-4 200g removed → slightly turbid (silty)
11:45	Set-up for development on IRZ-2
12:00	Call Chris Lutes + leave message. Then call
	Rich (Lowell) and discuss development. Foot
	valve surging method appears to be counter productive,
	as violent motion of whaler pump/winch will
	constantly stir up fine silt. Currently using
	rig/winch on IRZ-2 and very little volume
	of water being removed. Discuss possibility
	of using alternative method.
12:20	Ask Geologic if they have whale pumps with
	them. They do, but no tubing.
1:00P	Speak w/ Jeff Burdick about development. Agree
	that best way to develop will have to be
	using "whaler" pump to remove more turbid
	water, then use centrifugal to pick up any
	sediment at the well bottom.

ARCADIS GERAGHTY & MILLER

DAILY LOG

Well(s)______ Project/No. BN009900.0003.MA003 Page 2

Site Location Hanscom AFB

Prepared By J. Bonsteel

Date/Time 5/18/00	Description of Activities
1:20P	Spoke w/Rich (Lovell) + determine that best
	method to develop will be whaler pump (time
	vs. quality of using centrifugal doesn't add up).
	Will purge last 2 wells until "super-turbid"
	water removed.
	Developing IRZ-2.
2:05	Water from IRZ-2 clearing to slightly turbid (100g)
	Will pump 125g (TOTAL) out then start IRZ-3
2:20P	IRZ-2 125g removed slightly turbid
2:25P	Set up on IRZ-3
2:35P	Developing IRZ-3 (1st 15g clear)
3:30P	IRZ-3 85g removed slightly turbid

ARCADIS GERAGHTY & MILLER

Sample/Core Log

Boring/Well IRZ-1 Project/No. RN009900.0003 MA003 Page 1 of 1

Site Location Bedford, MA Drilling Started 5/15/00 Drilling Completed

Total Depth Drilled ____ Feet Hole Diameter 6 inches Type of Sample/Coring Device Splitspoon (44-46')

Length and Diameter of Coring Device Drive + Wash Casing Sampling Interval ____ feet

Land-Surface Elev. ____ feet ☐ Surveyed ☐ Estimated Datum ____

Drilling Fluid Used Potable Water Drilling Method Drive+Wash

Drilling Contractor GeoLogic Driller Mike Helper Mike

Prepared By J. Ronstiel Hammer Weight ____ Hammer Drop ____ ins.

Sample/Core Depth (feet below land surface) From	To	Core Recovery (feet)	Time/Hydraulic Pressure or Blows per 6 Inches	Sample/Core Description
0	1			Topsoil (sand-clay-grass)
1	10			Dk Brown / Gray f-m SAND, loose
10	20			Gray f. SAND, SILT + CLAY
20	33			Gray f. SAND + SILT
33	35			Denser SILT, GRAVEL + small COBBLES
35	44			TILL -- dense silt/clay (gray), small angular
				gravel
44	45		10,210	Very dense TILL (gray clay, some sand),
				f-m, moist (PID = 0.4 ppm)
				Top of rock @ 48.5'

919-544-4535
Chris Lutes

No. RN009900.0003.M1003 Page 2

Bedford (Hanscom AFB)

J. Rastrel

5/16/00 Description of Activities

0 Boulders encountered @ depth. Unable to drive casing further. Call Rich (Lowell) and confirm it is OK to set well in open borehole @ 48.5' (Bedrock).

13:05 Talk w/ Sam + go over progress.

13:55 Well bottom @ 48.4'
Screen 48.4' to 33.4'
Sand to 30.5'
Bentonite to 28.5'
5:05 Grout to grade

IRZ 1
Well Construction

Talk w/ Chris Lutes (NC) about well details + lab for grain size analysis

Talk w/ Chuck (Lowell) about development water storage/disposal. Will speak w/ Sam to see if he knows what agreement was reached w/ Tom Best.

6:00 Finish IRZ-1. Packing up rig + equipment

:45 Drop off samples @ Fed Ex.

ARCADIS GERAGHTY & MILLER

Sample/Core Log

Boring/Well IRZ-2 Project/No. ~~M000~~ RN0099001.0003 Page ____ of ____

Site Location Hascom AFB Site 1 Drilling Started 5/3/00 Drilling Completed ____

Total Depth Drilled 45 Feet Hole Diameter 8 inches Type of Sample/Coring Device split spoon

Length and Diameter of Coring Device 2' long 2" diameter Sampling Interval ____ feet

Land-Surface Elev. ____ feet ☐ Surveyed ☐ Estimated Datum ____

Drilling Fluid Used ____ Drilling Method augers

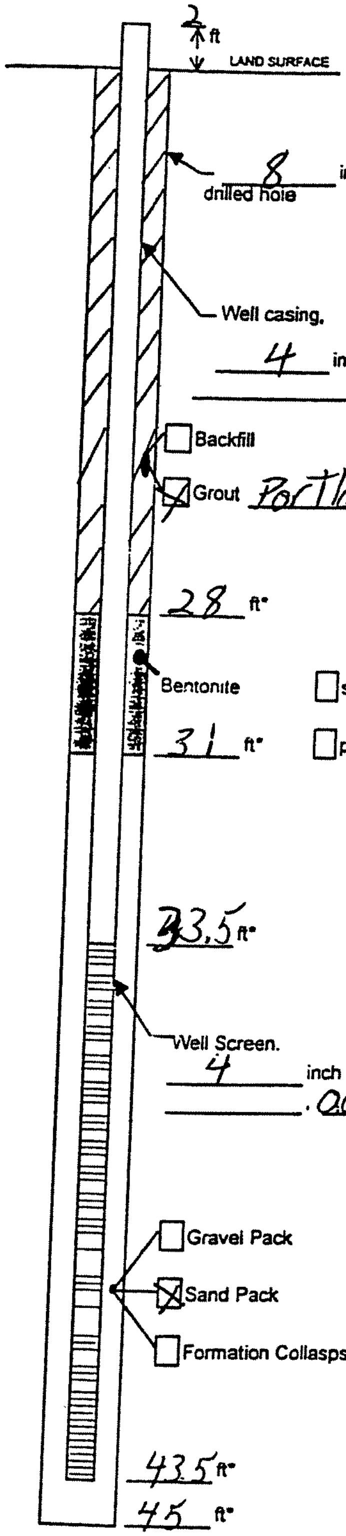
Drilling Contractor GeoLogic Driller Mike Helper Todd

Prepared By S Darrigrand Hammer Weight 140 Hammer Drop ____ ins.

Sample/Core Depth (feet below land surface) From	To	Core Recovery (feet)	Time/Hydraulic Pressure or Blows per 6 Inches	Sample/Core Description
0				ground surface - grassy, alongside drainage
				ditch
0	0.5			organic rich topsoil & roots
0.5	10			sand tan moist loose fine-med
				some gravel sized material rounded
10				water - sand saturated
10	19			same fine-med sand, saturated
19	25			sand - grey, saturated fine-med
25	31			sand & silt mostly fine grey saturated
31	39			suspected till layer augers encountering
				larger rocks
39	41	sampled		very poorly sorted layers of sand
			48-57-52-84	and silt, grey, tightly packed

ARCADIS GERAGHTY & MILLER

Well Construction Log
(Uncolsolidated)



8 inch diameter drilled hole

Well casing, 4 inch diameter.

☐ Backfill

☒ Grout Portland

28 ft*

Bentonite ☐ slurry

31 ft* ☐ pellets

33.5 ft*

Well Screen. 4 inch diameter

.001 slot

☐ Gravel Pack

☒ Sand Pack

☐ Formation Collaspse

43.5 ft*

45 ft*

Measuring Point is
Top of Well Casing
Unless Otherwise Noted.

* Depth Below Land Surface

Project AFCEE Well IRZ-2

Town/City Lexington

County State MA

Permit No.

Land-Surface Elevation and Datum:

feet ☐ Surveyed ☐ Estimated

Installation Date(s) 5/3/00

Drilling Method hollow stem auger

Drilling Contractor GeoLogic

Drilling Fluid water

Development Technique(s) and Date(s)

Fluid Loss During Drilling gallons

Water Removed During Development gallons

Static Depth to Water feet below M.P.

Pumping Depth to Water feet below M.P.

Pumping Duration hours

Yield gpm Date

Specific Capacity gpm/ft

Well Purpose

Remarks

Prepared by

ARCADIS GERAGHTY & MILLER

Sample/Core Log

Boring/Well TRZ-3 Project/No. RN00099002.0003. MA003 Page ____ of ____

Site Location AFCEE Drilling Started 5/5/00 Drilling Completed 5/8/00

Total Depth Drilled 54.5 Feet Hole Diameter 6 inches Type of Sample/ Coring Device splitspoon

Length and Diameter of Coring Device 2' spoon Sampling Interval ______ feet

Land-Surface Elev. ______ feet ☐ Surveyed ☐ Estimated Datum ______

Drilling Fluid Used water Drilling Method drive&wash

Drilling Contractor Geologic Driller Mike Helper Todd

Prepared By S Dorrigland Hammer Weight 140 Hammer Drop [illegible] ins.

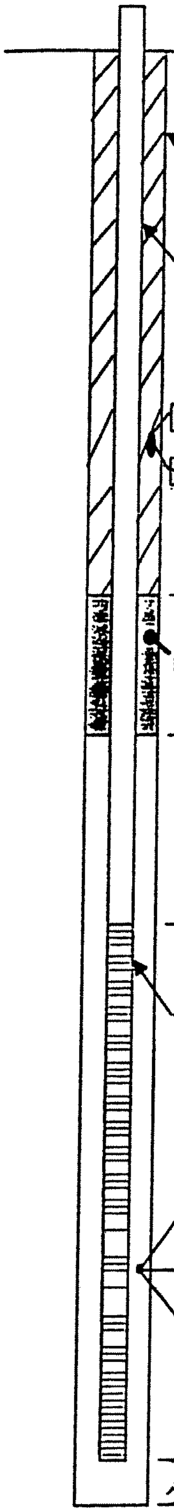
377 4425

Sample/Core Depth (feet below land surface) From	To	Core Recovery (feet)	Time/Hydraulic Pressure or Blows per 6 Inches	Sample/Core Description
0	10			sand tan fine-med grained loose moist
10				becoming wet top of water table
19	21			same sand
21	23			same sand grey in color
23	29			silty sand grey, fine sand & silt
				saturated
29	33			silty clay grey saturated low plastic
33	42			~~till~~ suspected till poorly sorted material
				washed up
42	44			boulder - black rock possibly
				bedrock material
44	46	1.4	68-73-86-64	~~to~~ poorly sorted material subrounded
		4 pm		cobbles & sand fine-coarse grey silt
45	48	2.3	62-58-80-52	mostly angular cobbles and tightly
				~~B~~ packed sand
54.5				bedrock

ARCADIS GERAGHTY & MILLER

Well Construction Log

(Uncolsolidated)



ft

LAND SURFACE

6 inch diameter drilled hole

Well casing,
2 inch diameter,
schedule 40

☐ Backfill
☒ Grout Portland

36 ft*

Bentonite ☐ slurry ☒ pellets

38 ft*

40 ft*

Well Screen.
4 inch diameter
.016 slot

☐ Gravel Pack
☒ Sand Pack
☐ Formation Collaspse

55 ft*

55.5 ft*

Measuring Point is
Top of Well Casing
Unless Otherwise Noted.

* Depth Below Land Surface

Project RN0099000.0003 Well IRZ-3

Town/City Bedford

County Middlesex State MA

Permit No. ____

Land-Surface Elevation and Datum:

____ feet ☐ Surveyed ☐ Estimated

Installation Date(s) 5/8/00

Drilling Method drive & wash/casing

Drilling Contractor GeoLogic

Drilling Fluid Water

Development Technicue(s) and Date(s)

Fluid Loss During Drilling ____ gallons

Water Removed During Development ____ gallons

Static Depth to Water ____ feet below M.P.

Pumping Depth to Water ____ feet below M.P.

Pumping Duration ____ hours

Yield ____ gpm Date ____

Specific Capacity ____ gpm/ft

Well Purpose ____

Remarks ____

Prepared by ____

Wellcstr.xls
3/16/98

ARCADIS GERAGHTY & MILLER

Sample/Core Log

Boring/Well IRZ-4 Project/No. RN009900.0003.MA003 Page 1 of 1

Site Location AFCEE

Drilling Started 5/9/00 Drilling Completed 5/11/00

Total Depth Drilled 51.2 Feet Hole Diameter 6 inches Type of Sample/Coring Device splitspoon

Length and Diameter of Coring Device 2' spoon Sampling Interval ____ feet

Land-Surface Elev. ____ feet ☐ Surveyed ☐ Estimated Datum ____

Drilling Fluid Used water Drilling Method drive&wash

Drilling Contractor GeoLogic Driller Mike Helper Mike

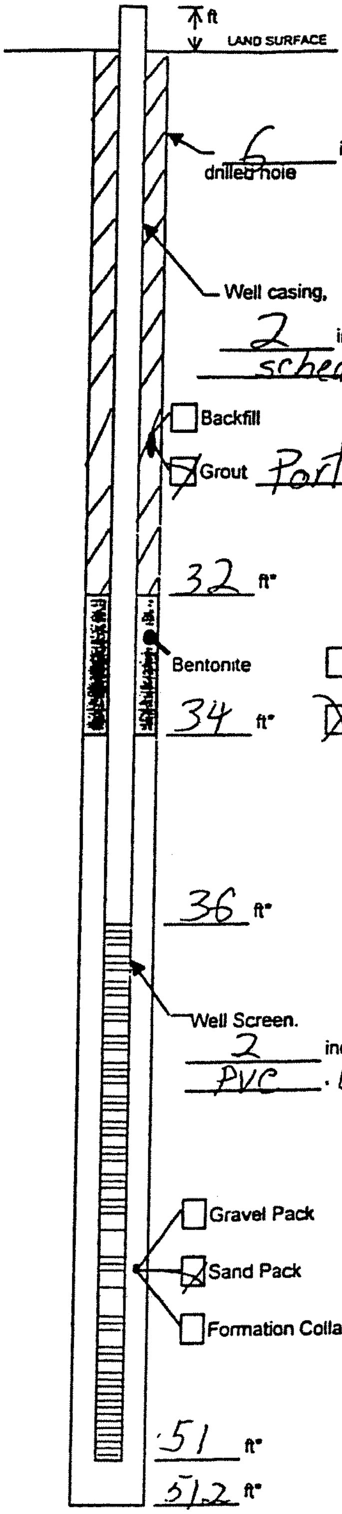
Prepared By S Darrigand Hammer Weight 140 Hammer Drop ____ ins.

Sample/Core Depth (feet below land surface) From	To	Core Recovery (feet)	Time/Hydraulic Pressure or Blows per 6 inches	Sample/Core Description
0	22			sand · tan & grey, fine-med grained, loose
10				saturated
12	24			sand & silt grey - fine, saturated
24	33			silty clay - grey, wet, low-med plastic
33	35.5			till · tightly packed sand & cobbles, poorly
				sorted
35.5	40			large boulder very dense material
44	46	18		till - sand · tightly packed wet
	PID-67.3			silt, and rock fragments
	FID-15.6			
51				bedrock

ARCADIS GERAGHTY & MILLER

Well Construction Log

(Uncolsolidated)



6 inch diameter drilled hole

Well casing,
2 inch diameter,
schedule 40

☐ Backfill
☒ Grout Portland

32 ft*

Bentonite ☐ slurry
34 ft* ☒ pellets

36 ft*

Well Screen.
2 inch diameter
PVC .010 slot

☐ Gravel Pack
☒ Sand Pack
☐ Formation Collaspse

51 ft*
51.2 ft*

Measuring Point is
Top of Well Casing
Unless Otherwise Noted.

* Depth Below Land Surface

Project RN0099100.0003 Well IRZ-4

Town/City Bedford

County Middlesex State MA

Permit No. ______

Land-Surface Elevation and Datum:

______ feet ☐ Surveyed

☐ Estimated

Installation Date(s) 5/1/00

Drilling Method drive & wash

Drilling Contractor GeoLogic

Drilling Fluid water

Development Technique(s) and Date(s)

Fluid Loss During Drilling ______ gallons

Water Removed During Development ______ gallons

Static Depth to Water ______ feet below M.P.

Pumping Depth to Water ______ feet below M.P.

Pumping Duration ______ hours

Yield ______ gpm Date ______

Specific Capacity ______ gpm/ft

Well Purpose ______

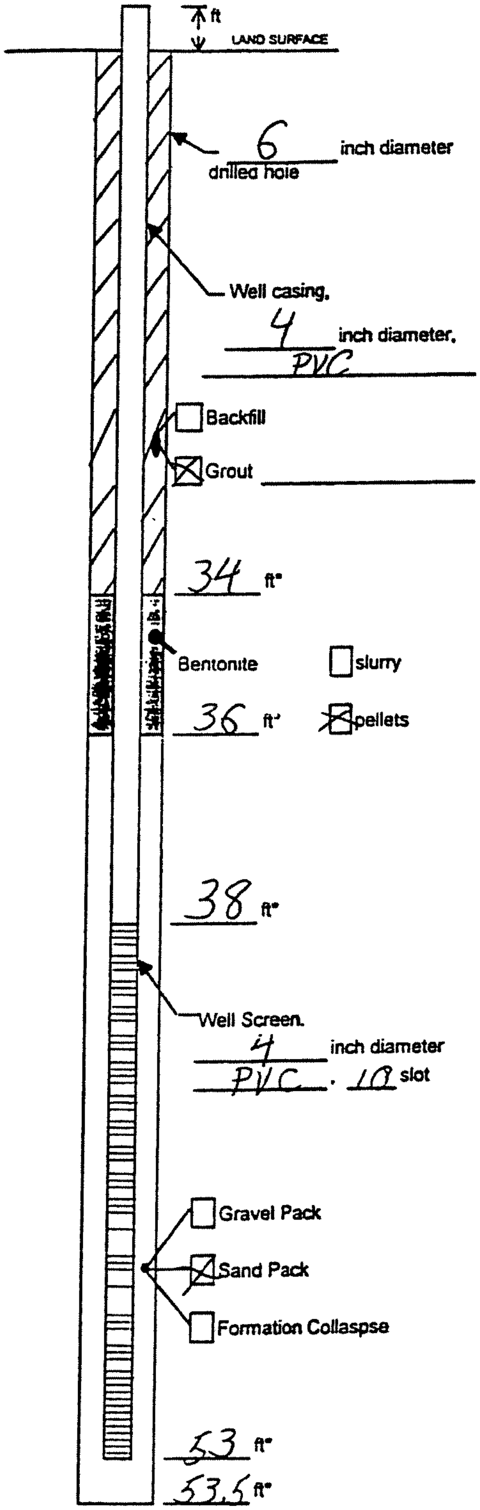
Remarks ______

Prepared by ______

Wellcstr.xls
3/16/98

ARCADIS GERAGHTY & MILLER

Well Construction Log
(Uncolsolidated)



6 inch diameter drilled hole

Well casing, 4 inch diameter, PVC

☐ Backfill

☒ Grout

34 ft*

Bentonite ☐ slurry

36 ft* ☒ pellets

38 ft*

Well Screen. 4 inch diameter PVC . 10 slot

☐ Gravel Pack

☒ Sand Pack

☐ Formation Collaspse

53 ft*

53.5 ft*

Measuring Point is
Top of Well Casing
Unless Otherwise Noted.

* Depth Below Land Surface

Project RN0099010012 Well IRZ-5

Town/City Bedford

County ________ State MA

Permit No. ________

Land-Surface Elevation and Datum:

________ feet ☒ Surveyed ☐ Estimated

Installation Date(s) 5/4/01 - 5/8/01

Drilling Method drive & wash

Drilling Contractor Geologic

Drilling Fluid water

Development Technique(s) and Date(s)

surge & pump - check valve
5/8/01

Fluid Loss During Drilling 200 gallons

Water Removed During Development 300 gallons

Static Depth to Water ________ feet below M.P.

Pumping Depth to Water 40.5 feet below M.P.

Pumping Duration 2.5 hours

Yield ≈2 gpm Date ________

Specific Capacity ________ gpm/ft

Well Purpose ________

Remarks ________

Prepared by S Darrigrand

Wellcstr.xls
3/16/98

ARCADIS GERAGHTY & MILLER

DAILY LOG

Well(s) ____ Project/No. RN009901 0012 MA003 Page ____

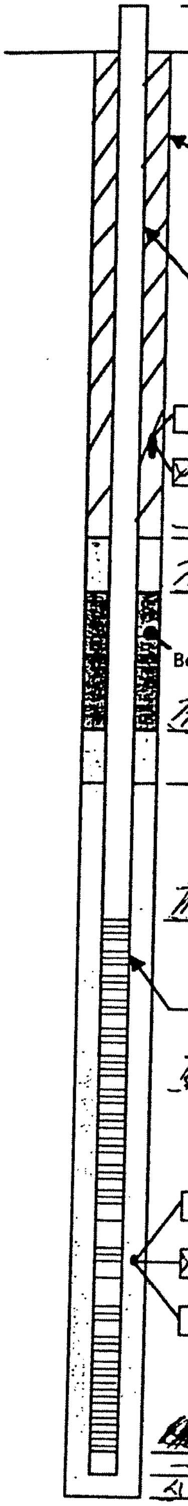
Site Location Hanscom AFB

Prepared By S Darrigrand

Date/Time	Description of Activities
5/8/01	
800	drillers onsite performing finishing
	work on well / Calibrated Horiba U-22
1000	began pumping on IRZ-Inj - very
	bubbly - flow through cell continually
	air locking
1110	turned up flow to keep water
	moving
1020	GeoLogic surging well
1100	~~beg~~ GeoLogic began pumping on
	IRZ-5 @ ≈2 gal/min
1140	sampled IRZ-Inj - very bubbly
	sampling difficult
1330	GeoLogic stopped pumping
	≈300 gal removed

ARCADIS GERAGHTY & MILLER

Well Construction Log
(Unconsolidated)



6 inch diameter drilled hole

Well casing,
4 inch diameter,
Sch 40PVC.

☐ Backfill
☒ Grout Portland

ft* ~~Choke Sand~~

27.8 ft

Bentonite ☐ slurry
30 ft* ☒ pellets

ft* ~~Choke Sand~~

34 ft* Top of Screen

Well Screen.
4 inch diameter
Sch 40PVC, 0.01 slot

☐ Gravel Pack
☒ Sand Pack
☐ Formation Collaspse

49 ft* Screen
ft* ~~Sump~~
[illegible] ft*

Measuring Point is
Top of Well Casing
Unless Otherwise Noted.

* Depth Below Land Surface

Project RN009900.0003 Well FRZ-Inj ~~Injection~~

Town/City Bedford

County Middlesex State MA

Permit No.

Land-Surface Elevation and Datum:

feet ☐ Surveyed
☐ Estimated

Installation Date(s) 5/1/00

Drilling Method Drive+Wash/Casing

Drilling Contractor Geologic

Drilling Fluid Water

Development Technique(s) and Date(s)

Fluid Loss During Drilling gallons

Water Removed During Development gallons

Static Depth to Water feet below M.P.

Pumping Depth to Water feet below M.P.

Pumping Duration hours

Yield gpm Date

Specific Capacity gpm/ft

Well Purpose

Remarks Grout to 4' bls

Prepared by J. B[illegible]

East Coast Drilling, Inc.

P. O. BOX 961 - WALLINGFORD, CONN. 06492

Bit # ______ Rig ______

Bit # ______ Rig ______

TO Haley & Aldrich, Inc.

ADDRESS Cambridge, Mass.

PROJECT NAME Hanscom Field

LOCATION Bedrock, Mass.

REPORT SENT TO Client

SAMPLES SENT TO Taken at site

PROJ. NO. 5833

OUR JOB NO. 85-231

SHEET ______ OF ______

DATE [illegible]

HOLE NO RAP1-6T

LINE & STA ______

OFFSET ______

GROUND WATER OBSERVATIONS

At 4.7 after 0 Hours

At ______ after ______ Hours

	CASING	SAMPLER	CORE BAR.
Type	HW		
Size I D	4"		
Hammer Wt			BIT
Hammer Fall			

SURFACE ELEV 123.6

DATE STARTED 11/15/85

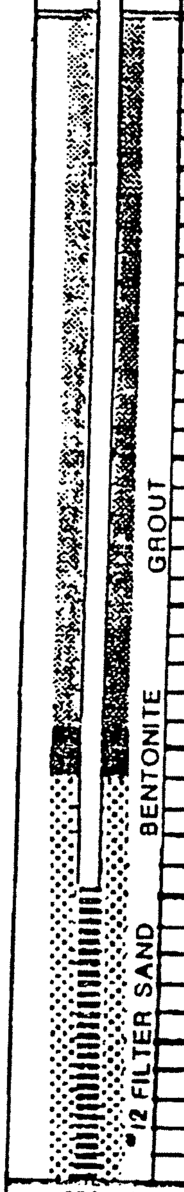
DATE COMPL. 11/18/85

BORING FOREMAN D. Quagliaroli

INSPECTOR I.S. Champess

SOILS ENGR. ______

LOCATION OF BORING See Plan



WELL INSTALLATION	Sample Depths From - To	Type of Sample	Blows per 6" on Sampler From 0-6	6-12	To 12-18	Moisture Density or Consist.	Strata Change Elev.	SOIL IDENTIFICATION Remarks include color, gradation, Type of soil etc. Rock-color, type, condition, hardness, Drilling time, seams and etc.	SAMPLE No	Pen	Rec
							0.5'	Topsoil			
								Gray-Brown fine Sand. *			
								- Outwash -			
							13.5'	Gray Silty fine Sand.			
								Gray Silt, little-trace coarse-fine Sand. *			
								Gray Silt, little coarse-fine Sand*			
								- Lacustrine -			
							29.0'	Gray Silty coarse-fine Sand.			
								Brown-Gray Silty coarse-fine Sand. *			
								- Till -			
								* See note on last page of this log.			

GROUND SURFACE TO 46.0' USED HW "CASING: THEN Bottom of boring 46.0'

Sample Type
D=Dry C=Cored W=Washed
UP=Undisturbed Piston
TP=Test Pit A=Auger V=Vane Test
UT=Undisturbed Thinwall

Proportions Used	
trace	0 to 10%
little	10 to 20%
some	20 to 35%
and	35 to 50%

140 lb Wt. x 30" fall on 2" O.D. Sampler

Cohesionless Density		Cohesive Consistency		
0-10	Loose	0-4	Soft	30 + Hard
10-30	Med. Dense	4-8	M/Stiff	
30-50	Dense	8-15	Stiff	
50 +	Very Dense	15-30	V-Stiff	

SUMMARY
Earth Boring 46.0'
Rock Coring ______
Samples ______

HOLE RAP1-6T

East Coast Drilling, Inc.

P. O. BOX 961 - WALLINGFORD, CONN. 06492

Bit # ______ Fig ______

Bit # ______ Fig ______

TO ______

PROJECT NAME ______

REPORT SENT TO ______

SAMPLES SENT TO ______

ADDRESS ______

LOCATION ______

PROJ. NO. ______

OUR JOB NO. ______

SHEET ______ OF ______

DATE ______

HOLE NO. RAP1-[illegible]

LINE & STA ______

OFFSET ______

GROUND WATER OBSERVATIONS

At ______ after ______ Hours

At ______ after ______ Hours

	CASING	SAMPLER	CORE BAR
Type			
Size I.D.			
Hammer Wt.			
Hammer Fall			BIT

SURFACE ELEV. ______

DATE STARTED ______

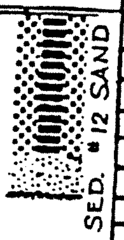
DATE COMPL. ______

BORING FOREMAN ______

INSPECTOR ______

SOILS ENGR. ______

LOCATION OF BORING

WELL INSTALLATION	Sample Depths From - To	Type of Sample	Blows per 6" on Sampler From 0-6	6-12	To 12-18	Moisture Density or Consist.	Strata Change Elev.	SOIL IDENTIFICATION Remarks include color, gradation, Type of soil etc. Rock-color, type, condition, hardness, Drilling time, seams and etc.	SAMPLE No	Pen	Rec
								Brown-Gray Silty coarse-fine Sand.			
								- Till -			
							46.0'				
								Bottom of boring at 46.0'			
								Note: No samples taken see boring RAP1-6R for detailed soils information. Installed 2" monitor well at 44.7' 15.0' screen 30.2' riser 150lbs. Sand 10lbs. Bentonite pellets 1 screw plug 1 protective steel sleeve with lock.			

GROUND SURFACE TO ______ USED ______ "CASING: THEN ______

Sample Type
D: Dry C: Cored W: Washed
UP: Undisturbed Piston
TP: Test Pit A: Auger V: Vane Test
UT: Undisturbed Thinwall

Proportions Used

trace	0 to 10%
little	10 to 20%
some	20 to 35%
and	35 to 50%

140 lb Wt. x 30" fall on 2" O.D. Sampler

Cohesionless Density

0-10	Loose
10-30	Med. Dense
30-50	Dense
50 +	Very Dense

Cohesive Consistency

0-4	Soft
4-8	M/Stiff
8-15	Stiff
15-30	V-Stiff
30 +	Hard

SUMMARY
Earth Boring ______
Rock Coring ______
Samples ______

HOLE NO RAP1-6

East Coast Drilling, Inc.

P. O. BOX 961 - WALLINGFORD, CONN. 06492

Bit # ______ Fig ______

Bit # ______ Fig ______

TO Haley & Aldrich, Inc.
PROJECT NAME Hanscom Field
REPORT SENT TO Client
SAMPLES SENT TO Taken at site

ADDRESS Cambridge, Mass.
LOCATION Bedford, Mass.
PROJ. NO. 5833
OUR JOB NO. 85-231

SHEET ______ OF ______
DATE 2/14/86
HOLE NO. RAP1-6R
LINE & STA
OFFSET

GROUND WATER OBSERVATIONS

At ______ after ______ Hours

At ______ after ______ Hours

	CASING	SAMPLER	CORE BAR.
Type	HW	S-S	
Size I.D.	4"	1 3/8"	
Hammer Wt.		140lbs.	BIT
Hammer Fall		30"	

SURFACE ELEV. 123.6
DATE STARTED 11/13/85
DATE COMPL. 11/13/85
BORING FOREMAN P. Wordell
INSPECTOR J.S. Chaness
SOILS ENGR.

LOCATION OF BORING: See Plan

WELL INSTALLATION	Sample Depths From - To	Type of Sample	Blows per 6" on Sampler From 0-6	6-12	To 12-18	Moisture Density or Consist.	Strata Change Elev.	SOIL IDENTIFICATION Remarks include color, gradation, Type of soil etc. Rock-color, type, condition, hardness, Drilling time, seams and etc.	SAMPLE No	Pen	Rec
	0.0'-2.0'	D	4	7	10 13	Moist M/Dense	.5'	Topsoil. Brown fine Sand.	1	2.0'	2.0'
	5.0'-7.0'	D	7	9	9 14	Moist M/Dense		Gray fine/Sand.	2	2.0'	1.5
	10.0'-12.0'	D	7	7	8 10	Moist M/Dense	13.5'	Brown fine Sand, trace Silt.	3	2.0'	1.5
	15.0'-17.0'	D	8	9	10 12	Moist M/Stiff		Gray Silt, trace-little fine Sand.	4	2.0'	2.0
	20.0'-22.0'	D	[illegible]	5	8 10	Moist /Stiff		Gray Silt, trace-little coarse-fine Sand.	5	2.0'	1.4
GROUT	25.0'-27.0'	D	6	6	7 9	Moist Stiff		Gray Silt, little coarse-fine Sand.	6	2.0'	2.0
	30.0'-32.0'	D	9	11	12 12	Moist M/Dense	34.0'	Gray Silty coarse-fine Sand.	7	2.0'	1.0
	35.0'-35.9'	D	39	102/.2'		Moist V/Dense		Gray coarse-fine sandySilt to sil coarse-fine Sand, coarse-fine Gravel Cobble and Boulders.	8	0.9'	.5'
	36.5'-40.0'	C							C1	3.5'	1.5
	40.0'-42.0'	D	37	42	50 55	Moist V/Dense		Gray Silty medium-fine Sand, trace-little Gravel, coarse Sand.	9	2.0'	1.5

GROUND SURFACE TO 45.8' USED HW "CASING: THEN Cored to 75.0'

Sample Type
D: Dry C: Cored W: Washed
UP: Undisturbed Piston
TP: Test Pit A: Auger V: Vane Test
UT: Undisturbed Thinwall

Proportions Used	
trace	0 to 10%
little	10 to 20%
some	20 to 35%
and	35 to 50%

140lb Wt. x 30" fall on 2" O.D. Sampler

Cohesionless Density	
0-10	Loose
10-30	Med. Dense
30-50	Dense
50 +	Very Dense

Cohesive Consistency		
0-4	Soft	30 + Hard
4-8	M/Stiff	
8-15	Stiff	
15-30	V-Stiff	

SUMMARY
Earth Boring 46.5'
Rock Coring 28.5'
Samples 10

HOLE NO RAP1-6

East Coast Drilling, Inc.

P. O. BOX 961 - WALLINGFORD, CONN. 06492

Bit # ______ Ftg ______

Bit # ______ Ftg ______

TO ______

PROJECT NAME ______

REPORT SENT TO ______

SAMPLES SENT TO ______

ADDRESS ______

LOCATION ______

PROJ. NO. ______

OUR JOB NO. ______

SHEET ______ OF ______

DATE ______

HOLE NO. RAP1-6R

LINE & STA ______

OFFSET ______

GROUND WATER OBSERVATIONS

At ______ after ______ Hours

At ______ after ______ Hours

	CASING	SAMPLER	CORE BAR.
Type			
Size I.D.			
Hammer Wt.			
Hammer Fall			NXT

SURFACE ELEV. ______

DATE STARTED ______

DATE COMPL. ______

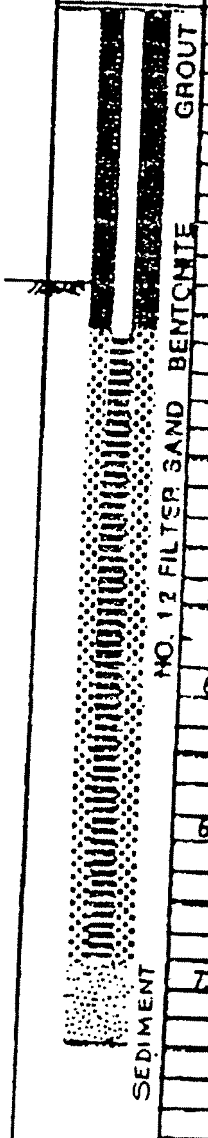
BORING FOREMAN ______

INSPECTOR ______

SOILS ENGR. ______

LOCATION OF BORING:

WELL INSTALLATION



Sample Depths From - To	Type of Sample	Blows per 6" on Sampler From 0-6	6-12	To 12-18	Moisture Density or Consist.	Strata Change Elev.	SOIL IDENTIFICATION Remarks include color, gradation, Type of soil etc. Rock-color, type, condition, hardness, Drilling time, seams and etc.	SAMPLE No	Pen	Rec
45.0'-45.8'	D	56	117/3"		Moist W/Dense		Brown Gray Silt, coarse-fine Sand, trace-little Gravel, trace Clay, Till.	10	.8'	.7'
50.0'-55.0'	C				ct	49.0'	Top of Bedrock			
					6		Granite.	C2	5.0'	4.9'
					5			RQD	-	63%
					5					
					4					
55.0'-56.0'	C				4		" "	C3	1.0'	1.0'
56.0'-59.8'	C				5		Brown Granite with numerous open seams, some filled with Silt.	C3	3.8'	3.1'
					4					
					6					
59.8'-63.8'	C				5		" "	C4	4.0'	3.8'
63.8'-68.8'	C						" "	C5	5.0'	3.0'
								RQD	-	87%
68.8'-73.8'	C						" "	C6	5.0'	3.9'
								RQD	-	100%
73.8'-75.0'	C						" "	C7	1.2'	1.1'
						75.0'	Bottom of boring 75.0' 1. Installed 2" PVC monitor well at 71.7' 20.2' screen 53.6' Riser			

GROUND SURFACE TO ______ USED ______ CASING: THEN ______

Sample Type
D: Dry C: Cored W: Washed
UP: Undisturbed Piston
TP: Test Pit A: Auger V: Vane Test
UT: Undisturbed Thinwall

Proportions Used	
trace	0 to 10%
little	10 to 20%
some	20 to 35%
and	35 to 50%

140 lb Wt. x 30" fall on 2" O.D. Sampler

Cohesionless Density		Cohesive Consistency			
0-10	Loose	0-4	Soft	30 +	Hard
10-30	Med. Dense	4-8	M/Stiff		
30-50	Dense	8-15	Stiff		
50 +	Very Dense	15-30	V-Stiff		

SUMMARY
Earth Boring ______
Rock Coring ______
Samples ______

HOLE NO RAP1-6

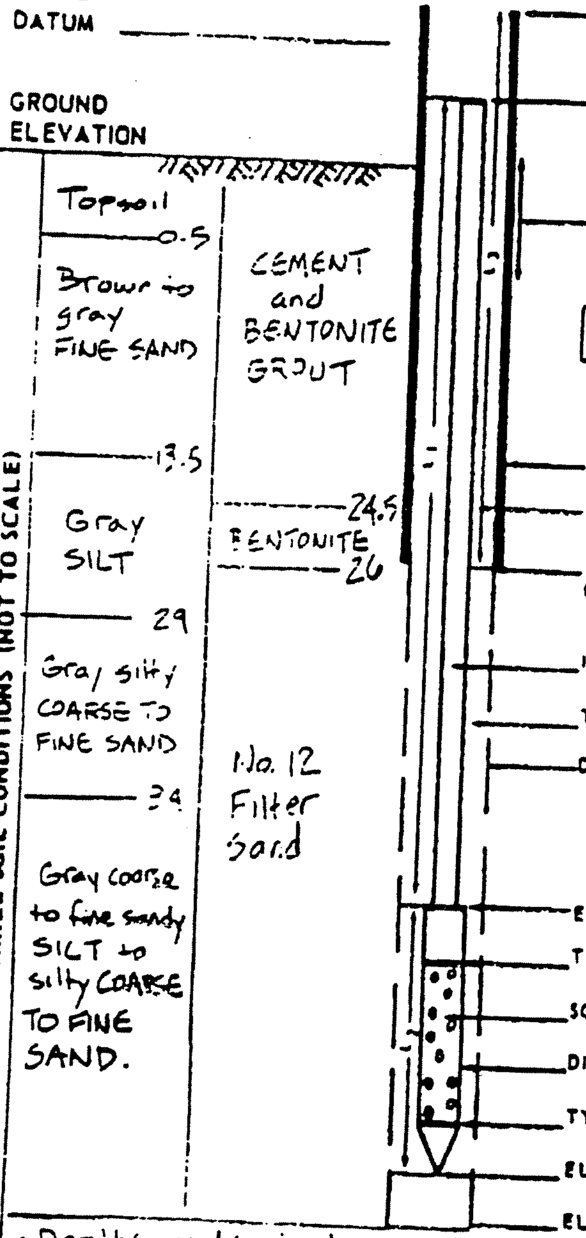
HALEY & ALDRICH, INC.
CAMBRIDGE, MASSACHUSETTS

GROUND WATER OBSERVATION WELL REPORT

PROJECT: Remedial Investigation
LOCATION: Hanscom Air Force Base, Massachusetts
CLIENT: U.S. Army Corps of Engineers
CONTRACTOR: East Coast Drilling, Inc.
DRILLER: D.J. Quagliaroli INSPECTOR: J.S. Chamness
INSTALLATION DATE 15 November 1985

FILE NO. [illegible]
WELL NO. RAP1-5T
BORING NO. RAP1-5T
LOCATION See Plan
SHEET 1 OF 1

SURVEY DATUM ____
GROUND ELEVATION



~~ELEVATION OR~~ STICKUP ABOVE ~~BELOW~~ GROUND SURFACE OF CASING ~~OR ROAD-WAY BOX~~ [illegible]
~~ELEVATION OR~~ STICKUP ABOVE ~~BELOW~~ GROUND SURFACE OF RISER PIPE. [illegible]
THICKNESS OF SURFACE SEAL 24.5 ft
TYPE OF SURFACE SEAL Grout
[INDICATE ALL SEALS SHOWING DEPTH, THICKNESS AND TYPE]
TYPE OF CASING Guard Pipe
INSIDE DIAMETER OF CASING 3.0 in.
ELEVATION DEPTH OF BOTTOM OF CASING 3.1 ft
INSIDE DIAMETER OF RISER PIPE 2.0 in
TYPE OF BACKFILL AROUND RISER Grout
DIAMETER OF BOREHOLE 4-½ in.
ELEVATION DEPTH OF BOTTOM OF RISER 29.6 ft
TYPE OF POINT OR MANUFACTURER Machine Slotted PVC
SCREEN GAUGE OR SIZE OF OPENINGS 0.010 in
DIAMETER OF WELLPOINT 2.0 in
TYPE OF BACKFILL AROUND POINT No. 12 Filter Sand
ELEVATION DEPTH OF BOTTOM OF POINT 44.7 ft.
ELEVATION DEPTH OF BOTTOM OF BOREHOLE 45.0 ft

• Depths indicated above are in feet.

[FIGURES REFER TO: EL. ____ DEPTH ✓]

[5.0 ft. LENGTH OF CASING L3] [30.2 ft LENGTH OF RISER PIPE (L1) + 15.1 ft. LENGTH OF POINT (L2) = 45.3 LENGTH]

H&A FORM 59 SEP 73

East Coast Drilling, Inc.

P. O. BOX 961 - WALLINGFORD, CONN. 06492

Bit # ______ Rig ______

Bit # ______ Rig ______

SHEET ______ OF ______

DATE ______

HOLE NO RAP1-6R

LINE & STA ______

OFFSET ______

TO ______

ADDRESS ______

PROJECT NAME ______

LOCATION ______

REPORT SENT TO ______

PROJ. NO. ______

SAMPLES SENT TO ______

OUR JOB NO. ______

GROUND WATER OBSERVATIONS

At ______ after ______ Hours

At ______ after ______ Hours

	CASING	SAMPLER	CORE BAR.
Type			
Size I D.			
Hammer Wt.			BIT
Hammer Fall			

SURFACE ELEV. ______

DATE STARTED ______

DATE COMPL. ______

BORING FOREMAN ______

INSPECTOR ______

SOILS ENGR. ______

LOCATION OF BORING:

DEPTH	Casing Blows per foot	Sample Depths From - To	Type of Sample	Blows per 6" on Sampler From 0-6	6-12	To 12-18	Moisture Density or Consist.	Strata Change Elev.	SOIL IDENTIFICATION Remarks include color, gradation, Type of soil etc. Rock-color, type, condition, hardness, Drilling time, seams and etc.	SAMPLE No	Pen	Rec
									2. Two water pressure tests conducted in Bedrock. 3. Grouted borehole above completed well installation.			

GROUND SURFACE TO ______ USED ______ "CASING: THEN ______

Sample Type

D: Dry C: Cored W: Washed

UP: Undisturbed Piston

TP: Test Pit A: Auger V: Vane Test

UT: Undisturbed Thinwall

Proportions Used

trace	0 to 10%
little	10 to 20%
some	20 to 35%
and	35 to 50%

140 lb Wt. x 30" fall on 2" O.D. Sampler

Cohesionless Density	
0-10	Loose
10-30	Med. Dense
30-50	Dense
50 +	Very Dense

Cohesive Consistency			
0-4	Soft	30 +	Hard
4-8	M/Stiff		
8-15	Stiff		
15-30	V-Stiff		

SUMMARY

Earth Boring ______

Rock Coring ______

Samples ______

HOLE NO RAP1-

HALEY & ALDRICH, INC.
CAMBRIDGE, MASSACHUSETTS

GROUND WATER OBSERVATION WELL REPORT

PROJECT: Remedial Investigation
LOCATION: Hanscom Air Force Base, Massachusetts
CLIENT: U.S. Army Corps of Engineers
CONTRACTOR: East Coast Drilling, Inc.
DRILLER: D.J. Quagliaroli INSPECTOR: V.S. [illegible]
INSTALLATION DATE 13-14 November 1985

FILE NO. 5377 01
WELL NO. RAP-03
BORING NO. RAP-03
LOCATION See Plan
SHEET 1 OF 1

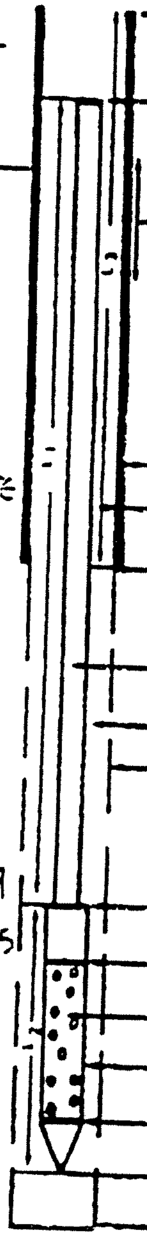
SURVEY DATUM ______

GROUND ELEVATION

SUMMARIZE SOIL CONDITIONS (NOT TO SCALE)

TOPSOIL	0.5
Brown to gray FINE SAND	13.5
Gray SILT	29
Gray silty COARSE TO FINE SAND	34
Gray coarse to fine sandy SILT to silty COARSE TO FINE SAND	49
BEDROCK	

CEMENT and BENTONITE GROUT	49
BENTONITE	50.5
No. 12 FILTER SAND	



~~ELEVATION OR~~ STICKUP ABOVE ~~BELOW~~ GROUND SURFACE OF CASING ~~OR ROAD WAY BOX~~	2.2 ft.
~~ELEVATION OR~~ STICKUP ABOVE ~~BELOW~~ GROUND SURFACE OF RISER PIPE.	2.1 ft.
THICKNESS OF SURFACE SEAL	49 ft.
TYPE OF SURFACE SEAL	Grout
[INDICATE ALL SEALS SHOWING DEPTH, THICKNESS AND TYPE]	
TYPE OF CASING	Guard Pipe
INSIDE DIAMETER OF CASING	3.0 in.
ELEVATION DEPTH OF BOTTOM OF CASING	2.8 ft.
INSIDE DIAMETER OF RISER PIPE	2.0 in.
TYPE OF BACKFILL AROUND RISER	Grout
DIAMETER OF BOREHOLE	4-1/2 in.
ELEVATION DEPTH OF BOTTOM OF RISER	51.5 ft.
TYPE OF POINT OR MANUFACTURER	Machine Slotted PVC
SCREEN GAUGE OR SIZE OF OPENINGS	0.020 in.
DIAMETER OF WELLPOINT	2.0 in.
TYPE OF BACKFILL AROUND POINT	No. 12 Filter Sand
ELEVATION DEPTH OF BOTTOM OF POINT	71.7
ELEVATION DEPTH OF BOTTOM OF BOREHOLE	73.0 ft.

• All depths indicated above are in feet.

[FIGURES REFER TO: EL. ____ DEPTH ✓]

[5.0 ft. LENGTH OF CASING L_3] [53.6 ft. LENGTH OF RISER PIPE (L_1) + 20.2 ft. LENGTH OF POINT (L_2) = 73.8 ft. LENGTH

H&A FORM 59

HALEY & ALDRICH, INC.
CAMBRIDGE
MASSACHUSETTS

TEST BORING REPORT

BORING NO. B239-MW

PROJECT HANSCOM A.F.B. LONG TERM SAMPLING PROGRAM, BEDFORD, MA
CLIENT U.S. ARMY CORPS OF ENGINEERS
CONTRACTOR M & R ENVIRONMENTAL DRILLING

FILE NO.	05833-065
SHEET NO.	1 of 2
LOCATION	N 537,549 E 657,673
ELEVATION	125.8
DATUM	NGVD
START	May 22, 1996
FINISH	May 22, 1996
DRILLER	P. Thornsbury
H & A REP	S. Goldkamp

ITEM	CASING	DRIVE SAMPLER	CORE BARREL
TYPE	HW	S	-
INSIDE DIAMETER (IN)	4	1 3/8	-
HAMMER WEIGHT (LB)	300	140	-
HAMMER FALL (IN)	24	30	-

DRILLING EQUIPMENT & PROCEDURES
RIG TYPE B-61 Mobile Truck rig
BIT TYPE Roller bit
DRILL MUD None
OTHER Cathead, Safety hammer. HW to 30.0 ft.

DEPTH (FT)	CASING BLOWS PER FT	SAMPLER BLOWS PER 6 IN	SAMPLE NUMBER & RECOVERY	SAMPLE DEPTH (FT)	ELEV./ DEPTH (FT)	VISUAL DESCRIPTION AND REMARKS
0						-TOPSOIL-
					124.8 1.0	Note: Cluster well with B240-MW. No sampling required. See boring log B240-MW for soil description. -FILL-
					121.8 4.0	-TOPSOIL-
5						
					120.3 5.5	-GLACIOFLUVIAL DEPOSITS-
					117.8 8.0	-GLACIOLACUSTRINE DEPOSITS-
10						
15						
					109.3 16.5	-GLACIOFLUVIAL DEPOSITS-
20						
		18 17	S1 12"	24.0 26.0		Medium dense rusty brown coarse to fine SAND, little fine gravel, trace silt
25						

WATER LEVEL DATA

DATE	TIME	ELAPSED TIME (HR)	DEPTH (FT) TO: BOTTOM OF CASING	BOTTOM OF HOLE	WATER

SAMPLE IDENTIFICATION
O OPEN END ROD
T THIN WALL TUBE
U UNDISTURBED SAMPLE
S SPLIT SPOON

SUMMARY	
OVERBURDEN (LIN FT)	30.0
ROCK CORED (LIN FT)	-
SAMPLES	1S

BORING NO. B239-MW

HALEY & ALDRICH, INC.
CAMBRIDGE
MASSACHUSETTS

TEST BORING REPORT

BORING NO. B239-MW
FILE NO. 05833-065
SHEET NO. 2 of 2

DEPTH (FT)	CASING BLOWS PER FT	SAMPLER BLOWS PER 6 IN	SAMPLE NUMBER & RECOVERY	SAMPLE DEPTH (FT)	ELEV./ DEPTH (FT)	VISUAL DESCRIPTION AND REMARKS
25		17				PID (HDSP) = 0.6/3.6 ppm
		16				
						-GLACIOFLUVIAL DEPOSITS-
30					95.8 30.0	Bottom of Exploration at 30.0 ft.

Located at site 1 recharge basin.
Installed monitoring well of 28.0 ft.

PID (HDSP): PID headspace reading collected from sample jars. Results presented as background reading/headspace reading.

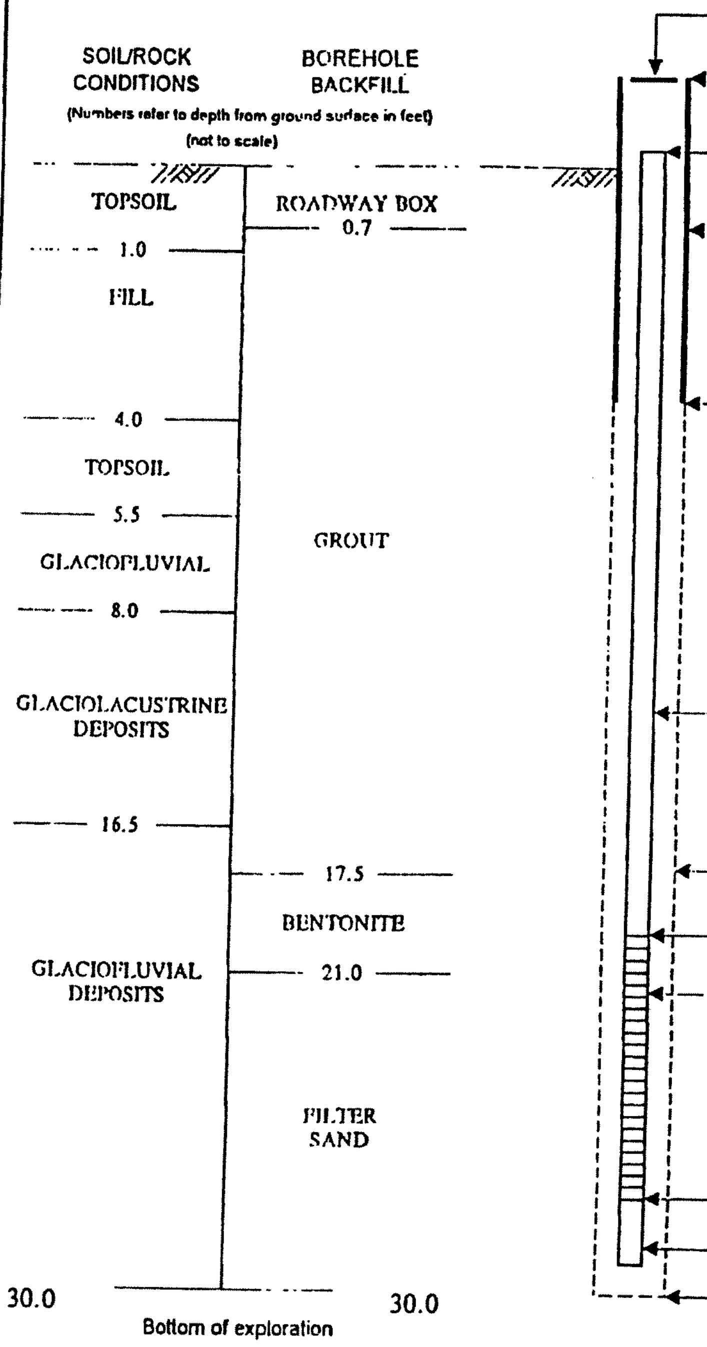
HALEY & ALDRICH

OBSERVATION WELL INSTALLATION REPORT

Observation Well	B239-MW
Test Boring	B239-MW
Installation Date	23 May 1996
Location	N 537548.5
	E 657673.1
H&A File No.	05833-065
H&A Rep.	S. Goldkamp

Project HANSCOM A.F.B. LONG TERM SAMPLING PROGRAM
City/State BEDFORD, MASSACHUSETTS
Client U.S. ARMY CORPS OF ENGINEERS
Contractor M&R ENVIRONMENTAL DRILLING
Foreman PHIL THORNSBURY

Ground El. 125.8
El. Datum NGVD



Type of protective cover/lock: Bolted Cover
Height of top of roadway box above ground surface 0.3 ft
Depth of top of riser pipe below ground surface 0.3 ft
Type of protective casing: Roadway Box
Length 1.0 ft
Inside diameter 5.0 in
Depth of bottom of roadway box 0.7 ft

Seals:

Type	Depth to top (ft)	Thickness (ft)
Cement	0.0	1.0
Grout	1.0	16.5
Bentonite	17.5	3.5

Type of riser pipe Solid PVC Sch. 40
Inside diameter of riser pipe 2.0 in
Type of backfill around riser: Seal
Diameter of borehole 4.5 in
Depth of top of wellpoint 23.0 ft
Type of point or manufacturer: Continuous Wrap PVC
Screen gauge or size of openings 0.010 in
Diameter of wellpoint 2.0 in
Type of backfill around point: Filter Sand
Depth of bottom of wellpoint 28.0 ft
Silt trap
Depth of bottom of borehole 30.0 ft

(Depths refer to ground surface)

Remarks: Plumbness test positive. Located at site 1 recharge basin.

HALEY & ALDRICH, INC.
CAMBRIDGE
MASSACHUSETTS

TEST BORING REPORT

BORING NO. B240-MW

PROJECT	HANSCOM A.F.B. LONG TERM SAMPLING PROGRAM, BEDFORD, MA
CLIENT	U.S. ARMY CORPS OF ENGINEERS
CONTRACTOR	M & R ENVIRONMENTAL DRILLING

FILE NO.	05833-065
SHEET NO.	1 of 3
LOCATION	N 537,553 E 657,677
ELEVATION	125.7
DATUM	NGVD
START	May 16, 1996
FINISH	May 18, 1996
DRILLER	P. Thornsbury
H & A REP	S. Goldkamp

ITEM	CASING	DRIVE SAMPLER	CORE BARREL
TYPE	PW/HW	S	HQ
INSIDE DIAMETER (IN)	5.0/4.0	1 3/8	2.5
HAMMER WEIGHT (LB)	300	140	-
HAMMER FALL (IN)	24	30	-

DRILLING EQUIPMENT & PROCEDURES

RIG TYPE B-61 Mobile Truck rig
BIT TYPE Roller bit
DRILL MUD None
OTHER Cathead/safety hammer; PW to 14.0 ft.; HW to 52.5 ft.

DEPTH (FT)	CASING BLOWS PER FT	SAMPLER BLOWS PER 6 IN	SAMPLE NUMBER & RECOVERY	SAMPLE DEPTH (FT)	ELEV./ DEPTH (FT)
0		1	S1	0.0	
		4	12"	1.0	124.7
		10	S1A	1.0	1.0
		12	12"	2.0	
		26	S2	2.0	
		41	24"	4.0	
		21			
		21			121.7
		3	S3	4.0	4.0
		5	15"	5.5	
5		3			120.2
		10	S3A	5.5	5.5
		12	4"	6.0	
		12	S4	6.0	
		13	12"	7.0	
		11	S4A	7.0	117.7
		6	6"	7.5	8.0
		10	S4B	7.5	
		15	4"	8.0	
		16	S5	8.0	
10		5	18"	10.0	
		14	S6	10.0	
		14	24"	12.0	
		18			
		6	S7	12.0	
		8	24"	14.0	
		9			
		10			
		3	S8	14.0	
15		5	12"	16.0	
		4			
		4			
		8	S9	16.0	109.2
		20	6"	18.0	16.5
		37			
		19			
		7	S10	18.0	
		12	13"	20.0	
		15			
20		15			
		18	S11	24.0	
25		12	12"	26.0	

VISUAL DESCRIPTION AND REMARKS

Stiff black silty LOAM, trace gravel, sand, roots, asphalt specks
-TOPSOIL-
PID (HDSP) = 0.6/3.2 ppm

Medium dense brown medium to fine SAND, little gravel, trace silt
PID (HDSP) = 0.6/3.0 ppm

D.O. except very dense
PID (HDSP) = 0.6/3.0 ppm
-FILL-

Stiff black fine sandy LOAM, trace roots
PID (HDSP) = 0.6/2.8 ppm
-TOPSOIL-

Medium dense gray silty fine SAND
PID (HDSP) = 0.6/2.6 ppm
-GLACIOFLUVIAL DEPOSITS-

Medium dense brown medium to fine SAND, little silt, trace coarse sand
PID (HDSP) = 0.6/2.4 ppm

S4B: Medium dense gray SILT, little gravel, sand
PID (HDSP) = 0.6/2.6 ppm

S5: Very stiff gray clayey SILT
PID (HDSP) = 0.6/2.4 ppm

D.O.
PID (HDSP) = 0.6/2.8 ppm
-GLACIOLACUSTRINE DEPOSITS-

Very stiff gray laminated SILT, little clay in seams
PID (HDSP) = 0.6/3.0 ppm

D.O. except stiff
PID (HDSP) = 0.6/2.6 ppm

S9: Very dense gray silty SAND, trace gravel
PID (HDSP) = 0.6/3.8 ppm

Medium dense brown fine SAND, trace silt
PID (HDSP) = 0.6/3.2 ppm

-GLACIOFLUVIAL DEPOSITS-

Dense rusty brown coarse to fine SAND, trace gravel

WATER LEVEL DATA

DATE	TIME	ELAPSED TIME (HR)	DEPTH (FT) TO: BOTTOM OF CASING	DEPTH (FT) TO: BOTTOM OF HOLE	DEPTH (FT) TO: WATER

SAMPLE IDENTIFICATION

O ░ OPEN END ROD
T ▥ THIN WALL TUBE
U ▩ UNDISTURBED SAMPLE
S ▨ SPLIT SPOON

SUMMARY

OVERBURDEN (LIN FT)	54.0
ROCK CORED (LIN FT)	15.0
SAMPLES	16S, 3C

BORING NO. B240-MW

HALEY & ALDRICH, INC.
CAMBRIDGE
MASSACHUSETTS

TEST BORING REPORT

BORING NO. B240-MW
FILE NO. 05833-065
SHEET NO. 2 of 3

DEPTH (FT)	CASING BLOWS PER FT	SAMPLER BLOWS PER 6 IN	SAMPLE NUMBER & RECOVERY	SAMPLE DEPTH (FT)	ELEV./ DEPTH (FT)	VISUAL DESCRIPTION AND REMARKS
25		19 22				PID (HDSP) = 0.6/6.2 ppm
30		15 17 19 22	S12 6"	29.0 31.0		Dense gray brown silty fine SAND, little gravel, trace clay PID (HDSP) = 0.6/5.4 ppm
						-GLACIOFLUVIAL DEPOSITS-
35		36 26 29 33	S13 9"	34.0 36.0		Very dense gray silty SAND, some gravel PID (HDSP) = 0.6/4.0 ppm
40		15 41 74 63	S14 13"	39.0 41.0	86.7 39.0	Layered hard gray CLAY and SILT PID (HDSP) = 0.6/1.2 ppm
45		27 56 87 101	S15 24"	44.0 46.0		Very dense gray coarse sandy SILT, little gravel, trace fine sand PID (HDSP) = 0.6/1.2 ppm
						-GLACIAL TILL DEPOSITS-
50		26 44 105	S16 6"	49.0 50.5		D.O. PID (HDSP) = 0.6/1.2 ppm
					73.2 52.5	Top of Bedrock at 52.5 ft. Roller bit taken to 54.0 ft.

NOTE: See Core Boring Report for Bedrock Description (page 3)

HALEY & ALDRICH, INC.
CAMBRIDGE,
MASSACHUSETTS

CORE BORING REPORT

BORING NO. B240-MW
FILE NO. 05833-065
SHEET NO. 3 OF 3

DEPTH (FT)	DRILLING RATE MIN./FT.	RUN NO.	DEPTH (FT)	RECOVERY/RQD IN.	RECOVERY/RQD %	WEATHERING	ELEV./DEPTH (FT)	VISUAL DESCRIPTION AND REMARKS
50								See pages 1 and 2 for Overburden Soils
							73.2 52.5	Top of Bedrock at 52.5 ft.
55	5 5 4 5 6	C1	54.0 59.0	60 42	100 70	Discol.		Hard, slightly weathered, extremely fractured to sound, mottled white-gray-brown, medium to very coarse grained PORPHYRITIC GRANITE. Joints very to moderately close, open, smooth to rough, planar and dipping of shallow angles. Joint surfaces weathered, oxidized. Observed healed joints dipping at high angles with numerous pits and vugs along them.
60	6 5 6 6 6	C2	59.0 64.0	60 56	100 93	Discol.		-BEDROCK-
65	6 8 7 7 5	C3	64.0 69.0	60 46	100 76	Discol.		
							56.7 69.0	Bottom of Exploration at 69.0 ft.

Located at site 1 recharge basin.
Installed monitoring well at 66.0 ft.

PID (HDSP): PID headspace reading collected from sample jars. Results presented as background reading/headspace reading.

HALEY & ALDRICH

OBSERVATION WELL INSTALLATION REPORT

Observation Well	B240-MW
Test Boring	B240-MW
Installation Date	22 May 1996
Location	N 537553.0 E 657676.8
H&A File No.	05833-065
H&A Rep.	S.Goldkamp

Project HANSCOM A.F.B. LONG TERM SAMPLING PROGRAM

City/State BEDFORD, MASSACHUSETTS

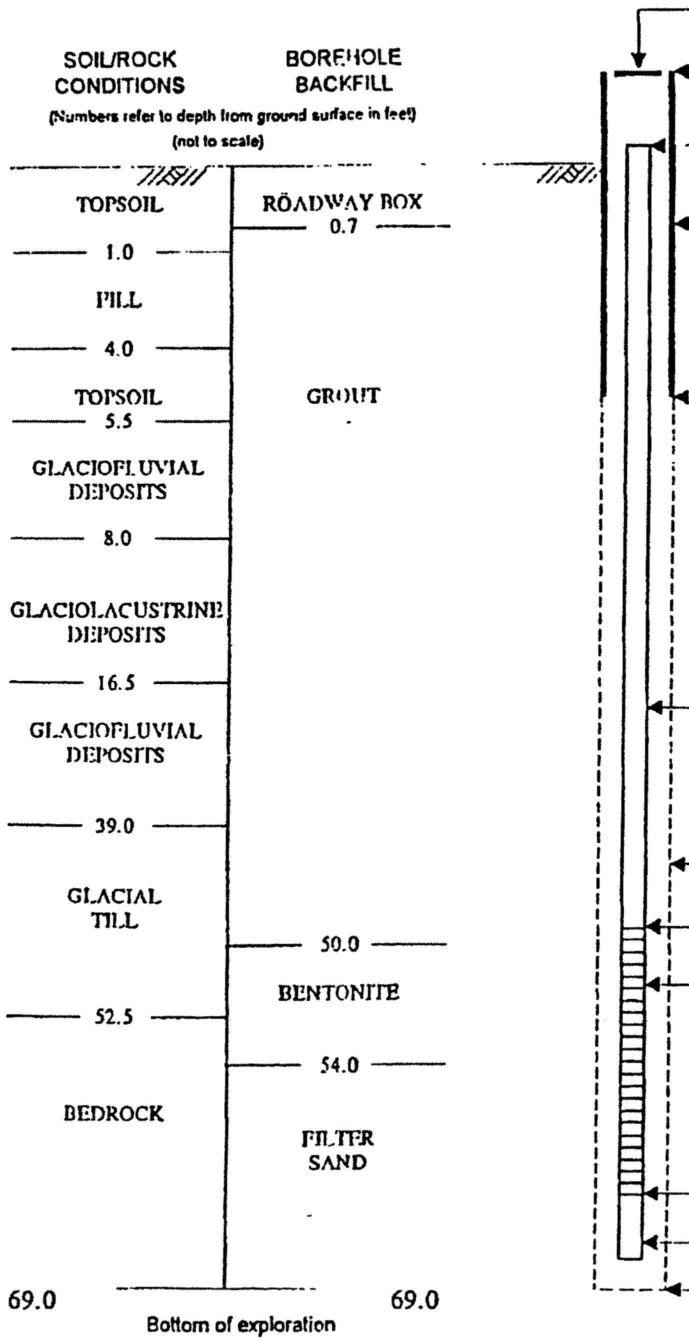
Client U.S. ARMY CORPS OF ENGINEERS

Contractor M&R ENVIRONMENTAL DRILLING

Foreman PHIL THORNSBURY

Ground El. 125.7

El. Datum NGVD



Type of protective cover/lock: Bolted Cover

Height of top of roadway box above ground surface 0.3 ft

Depth of top of riser pipe below ground surface 0.3 ft

Type of protective casing: Roadway Box

Length 1.0 ft

Inside diameter 5.0 in

Depth of bottom of roadway box 0.7 ft

Seals:

Type	Depth to top (ft)	Thickness (ft)
Cement	0.0	1.0
Grout	1.0	49.0
Bentonite	50.0	4.0

Type of riser pipe: Solid PVC Sch. 40

Inside diameter of riser pipe 2.0 in

Type of backfill around riser: Seal

Diameter of borehole 4.0 in

Depth of top of wellpoint 56.0 ft

Type of point or manufacturer: Continuous Wrap PVC

Screen gauge or size of openings 0.010 in

Diameter of wellpoint 2.0 in

Type of backfill around point: Filter Sand

Depth of bottom of wellpoint 66.0 ft

Silt trap

Depth of bottom of borehole 69.0 ft

(Depths refer to ground surface)

Remarks: Plumbness test positive. Located at site 1 recharge basin.

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HALEY & ALDRICH, INC.
CAMBRIDGE
MASSACHUSETTS

TEST BORING REPORT

BORING NO. B242-MW

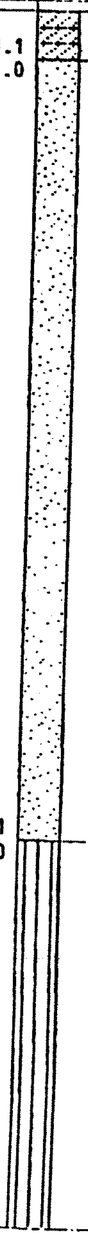
PROJECT	HANSCOM A.F.B. LONG TERM SAMPLING PROGRAM, BEDFORD, MA
CLIENT	U.S. ARMY CORPS OF ENGINEERS
CONTRACTOR	M & R ENVIRONMENTAL DRILLING

FILE NO.	05833-065
SHEET NO.	1 of 2
LOCATION	N 537,516 E 658,420
ELEVATION	122.1
DATUM	NGVD
START	May 30, 1996
FINISH	May 30, 1996
DRILLER	P. Thornsbury
H & A REP	W. Rubik

ITEM	CASING	DRIVE SAMPLER	CORE BARREL
TYPE	HW	S	-
INSIDE DIAMETER (IN)	4.0	1 3/8	-
HAMMER WEIGHT (LB)	300	140	-
HAMMER FALL (IN)	24	30	-

DRILLING EQUIPMENT & PROCEDURES

RIG TYPE B-61 Mobile
BIT TYPE Roller bit
DRILL MUD None
OTHER Safety hammer/Cathead; HW to 49.0 ft.



DEPTH (FT)	CASING BLOWS PER FT	SAMPLER BLOWS PER 6 IN	SAMPLE NUMBER & RECOVERY	SAMPLE DEPTH (FT)	ELEV./ DEPTH (FT)	VISUAL DESCRIPTION AND REMARKS
0						-TOPSOIL-
					121.1 1.0	Note: Cluster well with monitoring well B243-MW. No sampling required. See boring log B243-MW for soil description.
5						
10						-GLACIOFLUVIAL DEPOSITS-
15						
					105.1 17.0	
20						-GLACIOLACUSTRINE DEPOSITS-
25						

WATER LEVEL DATA

DATE	TIME	ELAPSED TIME (HR)	DEPTH (FT) TO: BOTTOM OF CASING	BOTTOM OF HOLE	WATER

SAMPLE IDENTIFICATION

O	▒	OPEN END ROD
T	▥	THIN WALL TUBE
U	■	UNDISTURBED SAMPLE
S	▨	SPLIT SPOON

SUMMARY

OVERBURDEN (LIN FT)	49.0
ROCK CORED (LIN FT)	-
SAMPLES	1S

BORING NO. B242-MW

HALEY & ALDRICH, INC.
CAMBRIDGE
MASSACHUSETTS

TEST BORING REPORT

BORING NO. B242-MW
FILE NO. 05833-065
SHEET NO. 2 of 2

DEPTH (FT)	CASING BLOWS PER FT	SAMPLER BLOWS PER 6 IN	SAMPLE NUMBER & RECOVERY	SAMPLE DEPTH (FT)	ELEV./ DEPTH (FT)	VISUAL DESCRIPTION AND REMARKS
25						
30						
35						-GLACIOLACUSTRINE DEPOSITS-
					83.2 38.9	
40						-GLACIOFLUVIAL DEPOSITS-
		25 47	S1 10"	44.0 46.0		Very dense gray gravelly medium to fine SAND, some silt, trace coarse sand PID (HDSP) = 0.4/0.8 ppm
45		23 23				
					73.1 49.0	Bottom of Exploration at 49.0 ft.

Located in northeastern area.
Installed monitoring well at 48.0 ft.

PID (HDSP): PID headspace reading collected from sample jars. Results presented as background reading/headspace reading.

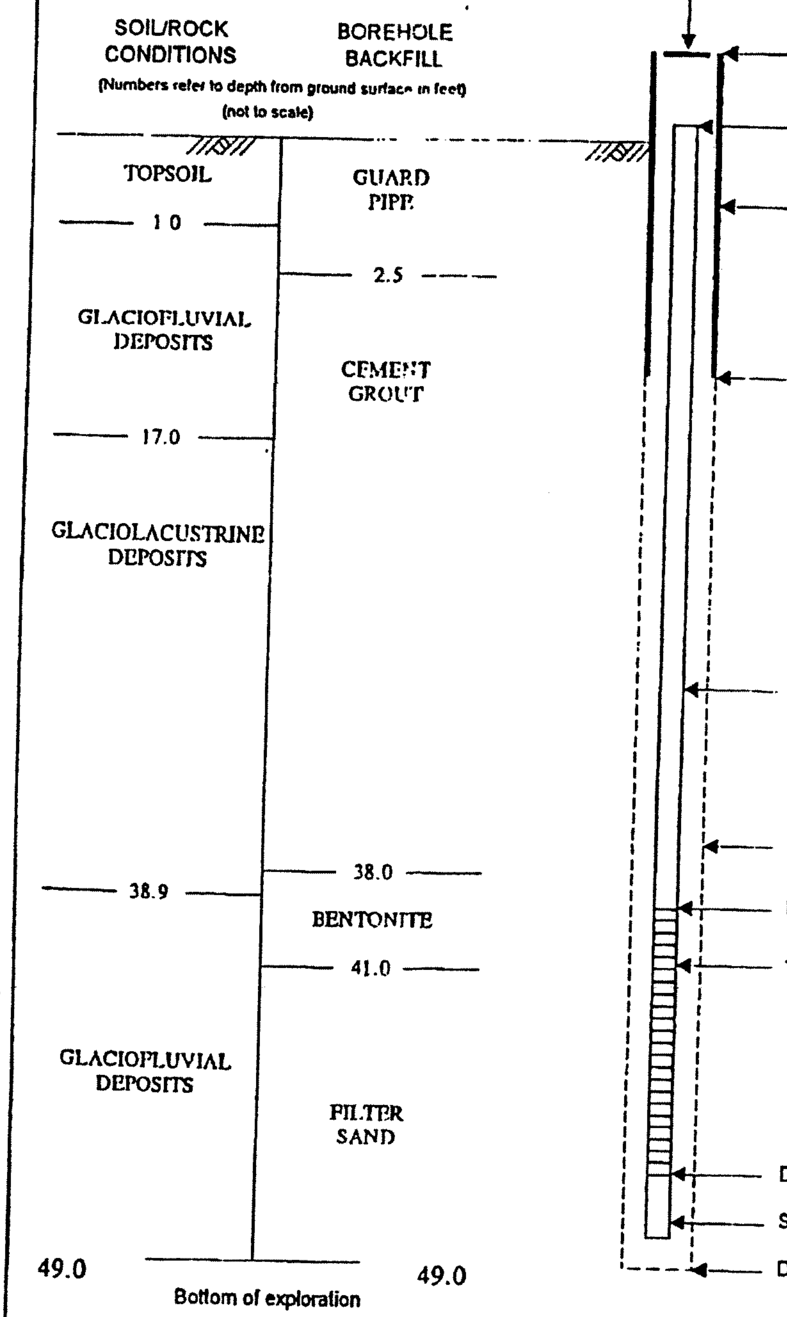
OBSERVATION WELL INSTALLATION REPORT

Observation Well B242-MW
Test Boring B242-MW
Installation Date 31 May 1996
Location N 537515.8
E 658419.9
H&A File No. 05833-065
H&A Rep. W. Rubik

HANSCOM A.F.B. LONG TERM SAMPLING PROGRAM

City/State BEDFORD, MASSACHUSETTS
Client U.S. ARMY CORPS OF ENGINEERS
Contractor M&R ENVIRONMENTAL DRILLING
Foreman P. THORNSBURY

Ground El. 122.1
El. Datum NGVD



Type of protective cover/lock: Cover/Padlock

Height of top of casing above ground surface 2.5 ft

Height of top of riser pipe above ground surface 2.0 ft

Type of protective casing: Steel Guard Pipe

Length 5.0 ft

Inside diameter 4.0 in

Depth of bottom of casing 2.5 ft

Seals:

Type	Depth to top (ft)	Thickness (ft)
Concrete	0.0	2.0
Cement Grout	2.0	36.0
Bentonite	38.0	3.0

Type of riser pipe: Solid PVC Sch. 40

Inside diameter of riser pipe 2.0 in

Type of backfill around riser: Seal

Diameter of borehole 4.5 in

Depth of top of wellpoint 43.0 ft

Type of point or manufacturer: Continuous Wrap PVC

Screen gauge or size of openings 0.010 in

Diameter of wellpoint 2.0 in

Type of backfill around point: Filter Sand

Depth of bottom of wellpoint 48.0 ft

Silt trap

Depth of bottom of borehole 49.0 ft

(Depths refer to ground surface)

Remarks: Plumbness test positive. Located at northeastern area.

HALEY & ALDRICH, INC.
CAMBRIDGE
MASSACHUSETTS

TEST BORING REPORT

BORING NO. **B243-MW**

PROJECT HANSCOM A.F.B. LONG TERM SAMPLING PROGRAM, BEDFORD, MA
CLIENT U.S. ARMY CORPS OF ENGINEERS
CONTRACTOR M & R ENVIRONMENTAL DRILLING

FILE NO. 05833-065
SHEET NO. 1 of 3
LOCATION N 537,515
E 658,426

ITEM	CASING	DRIVE SAMPLER	CORE BARREL	DRILLING EQUIPMENT & PROCEDURES
TYPE	PW/HW	S	HQ	RIG TYPE B-61 Mobile
INSIDE DIAMETER (IN)	5.0/4.0	1 3/8	2.5	BIT TYPE Roller bit
HAMMER WEIGHT (LB)	300	140	-	DRILL MUD None
HAMMER FALL (IN)	24	30	-	OTHER Safety hammer/Cathead; PW to 25.0 ft.; HW to 50.5 ft.

ELEVATION 122.2
DATUM NGVD
START May 28, 1996
FINISH May 29, 1996
DRILLER P. Thornsbury
H & A REP W. Rubik

DEPTH (FT)	CASING BLOWS PER FT	SAMPLER BLOWS PER 6 IN	SAMPLE NUMBER & RECOVERY	SAMPLE DEPTH (FT)	ELEV./DEPTH (FT)	VISUAL DESCRIPTION AND REMARKS
0		2 2	S1 9"	0.0 1.0	121.2 1.0	Soft black LOAM, little fine sand, root fibers -TOPSOIL- PID(SS) =0.4/0.4 ppm FID(HDSP) =0.4/0.4 ppm
		3 4	S1A 12"	1.0 2.0		S1A: Loose brown medium to fine SAND, trace root fibers PID (SS) = 0.4/0.4 ppm FID (HDSP) = 0.4/0.4 ppm
		2 4 6 7	S2 14"	2.0 4.0		S2: Loose to medium dense medium to fine SAND in partings PID (SS) = 0.4/0.4 ppm FID (HDSP) = 0.4/0.4 ppm -GLACIOFLUVIAL DEPOSITS-
5		2 3 4 4	S3 18"	4.0 6.0		S3: D.O. PID (SS) = 0.4/0.4 ppm FID (HDSP) = 0.4/0.5 ppm
		4 3 3 3	S4 15"	6.0 8.0		S4: Loose gray fine SAND in partings PID (SS) = 0.4/0.4 ppm FID (HDSP) = 0.4/0.5 ppm
		1 2 3 4	S5 11"	8.0 10.0		S5: D.O. PID (SS) = 0.4/0.4 ppm FID (HDSP) = 0.4/1.8 ppm
10		4 4 4 6	S6 16"	10.0 12.0		Loose gray-brown medium to fine SAND in partings PID (SS) = 0.4/0.4 ppm FID (HDSP) = 0.4/0.8 ppm
		5 5 6 6	S7 13"	12.0 14.0		Medium dense gray to rusty brown fine SAND in partings, little silt PID (SS) = 0.4/0.4 ppm FID (HDSP) = 0.4/0.8 ppm
15		1 1 4 7	S8 10"	14.0 16.0		Loose rusty brown medium to fine SAND in partings, little silt PID (SS) = 0.4/0.6 ppm FID (HDSP) = 0.4/3.2 ppm
		4 6	S9 12"	16.0 17.0	105.2 17.0	Medium dense gray to rusty brown coarse to fine SAND PID (SS) = 0.4/0.8 ppm FID (HDSP) = 0.4/1.8 ppm
		8 8	S9A 7"	17.0 18.0		S9A: Medium dense gray SILT in partings PID (SS) = 0.4/0.4 ppm FID (HDSP) = 0.4/0.8 ppm
		2 2 5 5	S10 16"	18.0 20.0		S10: D.O. except loose FID (SS) = 0.4/0.4 ppm FID (HDSP) = 0.4/0.6 ppm
20						-GLACIOLACUSTRINE DEPOSITS-
		5 5	S11 20"	24.0 26.0		Stiff gray SILT in partings, little clay in frequent seams
25						

WATER LEVEL DATA

DATE	TIME	ELAPSED TIME (HR)	DEPTH (FT) TO: BOTTOM OF CASING	DEPTH (FT) TO: BOTTOM OF HOLE	DEPTH (FT) TO: WATER
5-28-96	07:30	0	4.0	6.0	4.0

SAMPLE IDENTIFICATION

O	▨	OPEN END ROD
T	▥	THIN WALL TUBE
U	■	UNDISTURBED SAMPLE
S	▨	SPLIT SPOON

SUMMARY

OVERBURDEN (LIN FT)	54.0
ROCK CORED (LIN FT)	15.0
SAMPLES	16S, 3C

BORING NO. **B243-MW**

TEST BORING REPORT

BORING NO. B243-MW
FILE NO. 05833-065
SHEET NO. 2 of 3

DEPTH (FT)	CASING BLOWS PER FT	SAMPLER BLOWS PER 6 IN	SAMPLE NUMBER & RECOVERY	SAMPLE DEPTH (FT)	ELEV./ DEPTH (FT)	VISUAL DESCRIPTION AND REMARKS
25		6 8				PID (SS) = 0.4/0.4 ppm PID (HDSP) = 0.4/0.8 ppm
30		4 6 6 4	S12 24"	29.0 31.0		D.O. PID (SS) = 0.4/0.4 ppm PID (HDSP) = 0.4/0.8 ppm -GLACIOLACUSTRINE DEPOSITS-
35		4 6 6 5	S13 22"	34.0 36.0		Stiff gray SILT in partings, little clay in frequent seams PID (SS) = 0.4/0.4 ppm PID (HDSP) = 0.4/1.4 ppm
					83.3 38.9	
40		9 9 9 9	S14 9"	39.0 41.0		Medium dense gray silty fine SAND, little gravel, medium sand PID (SS) = 0.4/0.6 ppm PID (HDSP) = 0.4/1.2 ppm -GLACIOFLUVIAL DEPOSITS-
45		48 48 49 36	S15 15"	44.0 46.0		D.O. except very dense, with occasional cobble PID (SS) = 0.4/0.8 ppm PID (HDSP) = 0.4/1.0 ppm
50		96 107 100/5"	S16 0"	49.0 50.4		No recovery, pushing cobble Top of Bedrock at 50.4 ft.
					71.8 50.4	Note: Explored with roller bit to 54.0 ft. to confirm Bedrock -BEDROCK- See Page 3 for Bedrock Description

HALEY & ALDRICH, INC.
CAMBRIDGE,
MASSACHUSETTS

CORE BORING REPORT

BORING NO. B243-MW
FILE NO. 05833-065
SHEET NO. 3 OF 3

DEPTH (FT)	DRILLING RATE MIN./FT.	RUN NO.	DEPTH (FT)	RECOVERY/RQD IN.	RECOVERY/RQD %	WEATH-ERING	ELEV./ DEPTH (FT)	VISUAL DESCRIPTION AND REMARKS
45								See Pages 1-2 for overburden soils
								Top of Bedrock at 50.4 ft.
50							50.4	
								-BEDROCK-
	5	C1	54.0 59.0	58 58	97 97	Discol.		Hard, very slight weathered, slighty fractured to sound, mottled white-gray-pink, medium to coarse grained GRANITE. Joints, close to wide, open, smooth to rough, planar and dipping at shallow angles. Joint surfaces slightly weathered, oxidized, some with very thin clay coating.
55	6							
	6							
	6							
	6							
	7	C2	59.0 64.0	58 58	97 97	Discol.		
60	6							
	6							
	8							
	6							
	4	C3	64.0 69.0	60 45	100 75	Discol.		C3: D.O. except slightly weathered, extremely fractured to sound. Joints very close to close, open, weathered and oxidized. Some joints with sand infillings.
65	4							
	5							Note: Rapidly loosing water below 64.0 ft.
	4							
	4							
							69.0	Bottom of Exploration at 69.0 ft.
								Located in northeastern area. Installed monitoring well at 68.0 ft.
								PID (SS): PID reading collected from open split spoon. Results presented as background reading/split spoon reading. PID (HDSP): PID headspace reading collected from sample jars. Results presented as background reading/headspace reading.

HALEY & ALDRICH

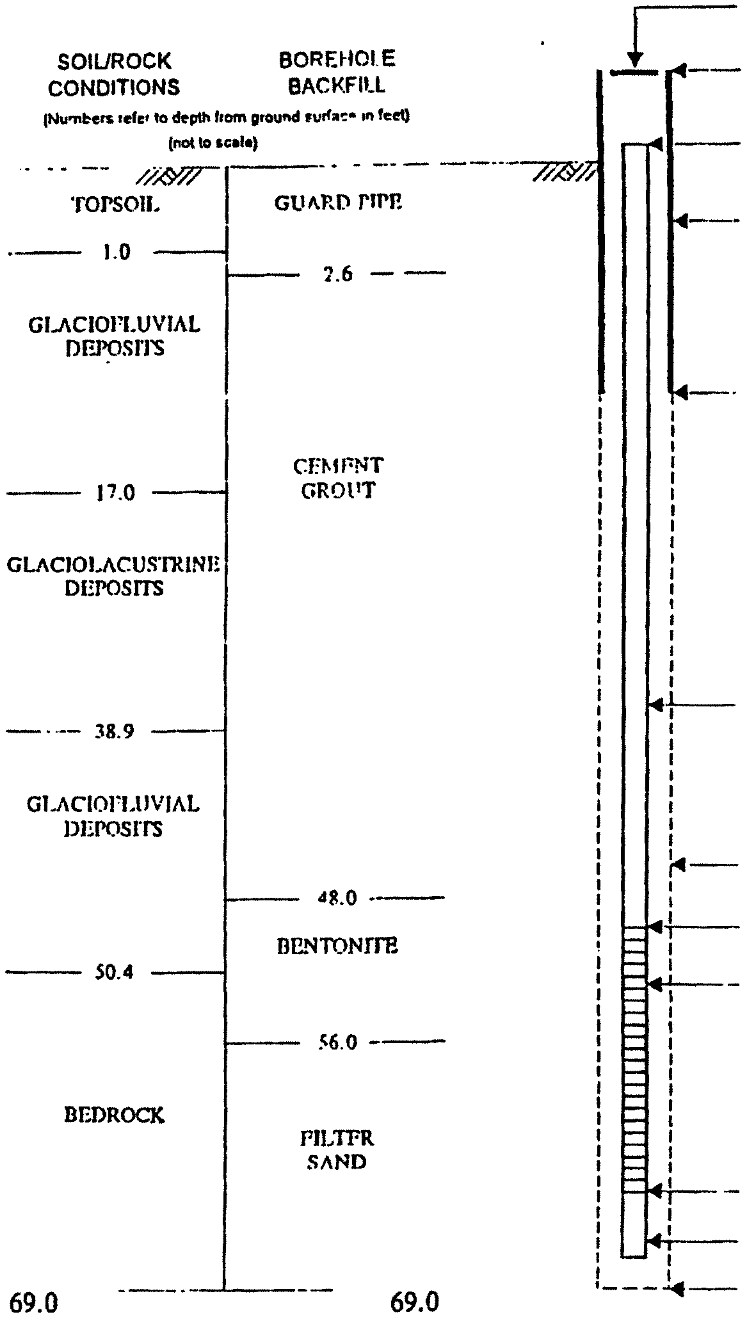
OBSERVATION WELL INSTALLATION REPORT

Observation Well	B243-MW
Test Boring	B243-MW
Installation Date	29 May 1996
Location	N 537514.8 E 658425.8
H&A File No.	05833-065
H&A Rep.	W. Rubik

Project	HANSCOM A.F.B. LONG TERM SAMPLING PROGRAM
City/State	BEDFORD, MASSACHUSETTS
Client	U.S. ARMY CORPS OF ENGINEERS
Contractor	M&R ENVIRONMENTAL DRILLING
Foreman	P. THORNSBURY

Ground El. 122.2

El. Datum NGVD



69.0 Bottom of exploration 69.0

Type of protective cover/lock: Cover/Padlock

Height of top of casing above ground surface 2.4 ft

Height of top of riser pipe above ground surface 2.0 ft

Type of protective casing: Steel Guard Pipe

Length 5.0 ft

Inside diameter 4.0 in

Depth of bottom of casing 2.6 ft

Seals:

Type	Depth to top (ft)	Thickness (ft)
Concrete	+0.5	2.0
Cement Grout	0.0	48.0
Bentonite	48.0	8.0

Type of riser pipe: Solid PVC Sch. 40

Inside diameter of riser pipe 2.0 in

Type of backfill around riser: Seal

Diameter of borehole 4.0 in

Depth of top of wellpoint 58.0 ft

Type of point or manufacturer: Continuous Wrap PVC

Screen gauge or size of openings 0.010 in

Diameter of wellpoint 2.0 in

Type of backfill around point: Filter Sand

Depth of bottom of wellpoint 68.0 ft

Silt trap

Depth of bottom of borehole 69.0 ft

(Depths refer to ground surface)

Remarks: Plumbness test positive. Located at northeaster area.

Appendix A-4b

Authorization to Leave Monitoring Wells in Place

From: Best Thomas Civ 66 CES/CEVR [Tom.Best@hanscom.af.mil]
Sent: Friday, January 31, 2003 2:47 PM
To: 'Lutes, Chris'; Best Thomas Civ 66 CES/CEVR
Cc: Hansen Jerry E Civ AFCEE/ERS; Gordon, Glen; Frizzell, Angela
Subject: RE: Hanscom IRZ Report/Wells

Sorry I haven't got back to you sooner - in general I have little to add in the way of comments - in regards to de-mob, yes we want to keep the wells as is - I do not foresee any requirements of ARCADIS in the transfer of the wells. Just walk away. Would like to get a type version of the boring & well logs but this is not imperative.

Comment - page 12, para 1.3.2 next to last sentence of 1st subpara - add "a former fire training area" after site 1. You do identify it as such later but I think it helps a reader to introduce it here, especially since most in the Air Force know exactly what was done at a fire training area.

Page 83, para 7.1 - change last 2 sentences of 1st para to read: A pre-NPL "Remedial Action Plan" for what is now NPL Operable Unit 1 (which includes Site 1) was approved and implemented in 1887. Subsequently, in October 2000 an Interim Record of Decision was issued for NPL Operable Unit 1 to continue operation of the existing dynamic groundwater collection and treatment system. MADEP concurred with the Interim Record of Decision.

last para, 1st sentence - change to .... Hanscom Field/Hanscom AFB boundaries....

That's all I have.

-----Original Message-----
From: Lutes, Chris [mailto:CLutes@arcadis-us.com]
Sent: Wednesday, January 22, 2003 11:17 AM
To: Best Thomas Civ 66 SPTG/CEVR
Cc: Hansen,Jerry (E-mail); Gordon, Glen; Frizzell, Angela
Subject: Hanscom IRZ Report/Wells

Dear Tom -

Have you had a chance to review the draft Hanscom report we issued in November? We have received ESTCP and AFCEE comments and are revising the report now, so it would be a good time to incorporate any comments you might have.

Thinking ahead to demobilization of the IRZ demonstration project at Hanscom after the rebound round we plan to do in 6 months or so, we are assuming you would like to keep and maintain the one injection and five monitoring wells, rather then having them decommissioned by us after the rebound round. If you would like to keep them, do you foresee any other requirements of ARCADIS involved in the transfer of the wells to you? We need to include our plans for these wells in a new demobilization section of the final report, so your comments will be appreciated.

Thanks,
Chris

Appendix A-5

Survey Data

MERIDIAN
ENGINEERING, INC.
PROFESSIONAL CIVIL ENGINEERS, LAND SURVEYORS & LANDSCAPE ARCHITECTS

VIA: U.S. MAIL

October 16, 2002

Mr. Brian Therriault
Arcadis G & M, Inc.
175 Cabot Street
Suite 400
Lowell, Massachusetts 01854

Re: Arcadis Project No. RN009901.0012
Hanscom Airforce Base

Dear Brian:

This letter is relative to Arcadis project No. RN009901.0012, more specifically well elevations for well IRZ-INJ at Hanscom Air Force Base.

Top of outer casing = 123.91

Top of inner casing = 123.67

Ground elevation @ well = 123.9±

As requested all above elevations are based on the National Geodetic Vertical datum of 1929 (NGVD29).

Should you have any questions or need additional services please do not hesitate to call.

Sincerely,

MERIDIAN ENGINEERING, INC.

Christopher P. Nicholas

PS Invoice will follow

CPN\jmd\F:\~\3663\WORD\letters\Arcadis (021016).doc

DANVERS
98 High Street
Danvers, MA 01923-3189
P: (978) 739-9130 • F: (978) 739-9140

www.meridianengineering.com
mei@meridianengineering.com

WESTBOROUGH
69 Milk Street, Suite 302
Westborough, MA 01581-1227
P: (508) 871-7030 • F: (508) 871-7039

Printed on Recycled Paper

HANSCOM A.F.B. OBSERVATION WELLS
PREPARED FOR ARCADIS GERAGHTY & MILLER, INC.
INSTALLATION RESTORATION PROGRAM

May 14, 2001

DESCRIPTION	NORTHING	EASTING	GROUND ELEVATION	TOP OF PVC (INNERCASING) ELEVATION
IRZ-5	537428.9	658206.1	125.2+/-	127.98
B-239	537548.5	657673.2	125.9+/-	125.68
RAP 1-6-R	537420.7	658082.9	123.4+/-	125.64
RAP 1-6-S	537430.6	658081.2	123.5+/-	125.00*
RAP 1-6-T	537417.7	658074.4	123.7+/-	125.49*

NOTES:

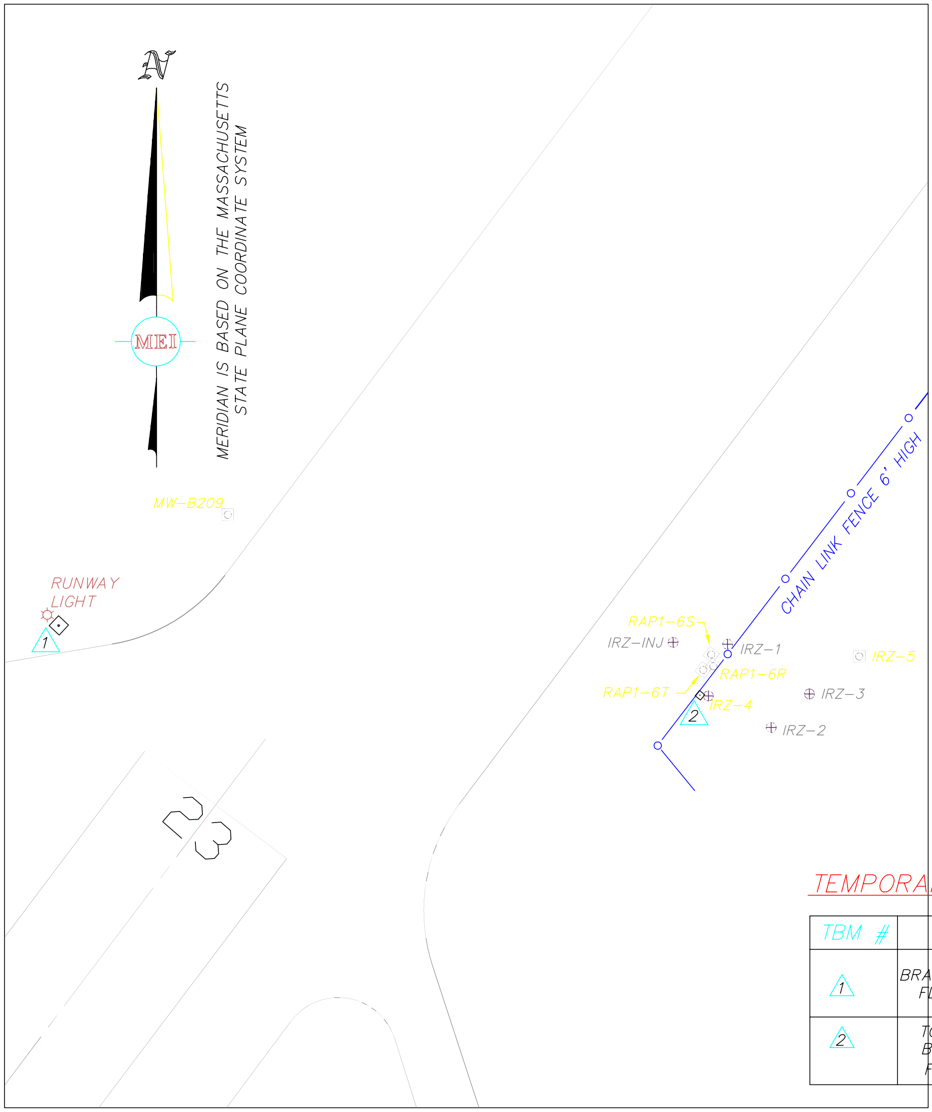
1. ELEVATIONS DEPICTED ARE BASED UPON THE NATIONAL GEODETIC VERTICAL DATUM (N.G.V.D.) OF 1929.

2. HORIZONTAL LOCATIONS OF THE WELLS ARE BASED UPON THE MASSACHUSETTS STATE PLANE COORDINATE SYSTEM (1927 NORTH AMERICAN DATUM).

3. THE FIELD SURVEY TO LOCATE THE WELLS WAS PERFORMED ON THE GROUND BY MERIDIAN ENGINEERING, INC. ON MAY 9, 2001.

* ELEVATION OF CROSS-CUT SET ON OUTER CASING.

KED\eew:jjm\F:\~\3663\survey\Observation Wells1 (excel) N.B 162G, P. 20



MERIDIAN IS BASED ON THE MASSACHUSETTS STATE PLANE COORDINATE SYSTEM

LEGEND:

☐ OBSERVATION WELL LOCATED BY MERIDIAN ENGINEERING, INC. (MEI)

⊕ SHADED WELLS WERE PREVIOUSLY LOCATED BY MEI.

NOTES:

1. THE SOLE PURPOSE OF THIS PLAN IS TO DEPICT THE LOCATION OF OBSERVATION WELLS AS PROVIDED BY ARCADIS GERAGHTY & MILLER, INC. AND LOCATED BY MERIDIAN ENGINEERING, INC. THE LOCATION OF ALL OTHER FEATURES, SUCH AS BUILDINGS, ROADS, FENCES, ETC. IS FOR ILLUSTRATIVE PURPOSES ONLY AND HAS BEEN PROVIDED BY THE CIVIL ENGINEERING DEPARTMENT OF HANSCOM AIR FORCE BASE.
2. THE FIELD SURVEY TO LOCATE MONITORING WELLS WAS PERFORMED ON THE GROUND BY MERIDIAN ENGINEERING, INC. ON DECEMBER 1, 2000, AND MAY 9, 2001.
3. HORIZONTAL LOCATION OF THE MONITORING WELL ARE BASED UPON THE MASSACHUSETTS PLANE COORDINATE SYSTEM (1927 NORTH AMERICAN DATUM).
4. ELEVATIONS DEPICTED ARE BASED UPON THE NATIONAL GEODETIC DATUM (N.G.V.D.) OF 1929.
5. STARTING BENCHMARK STATION RAY, 1957 AZMUTH #2 ELEVATION = 126.99
   STARTING BENCHMARK STATION 54AD ELEVATION = 218.530
   STARTING BENCHMARK STATION ARP 1963 ELEVATION = 126.489
6. STARTING HORIZONTAL CONTROL STATION RAY, 1957-AZMUTH #2 A MASSACHUSETTS DEPARTMENT OF PUBLIC WORKS TRAVERSE DISK STAMPED "RAY, 1957 AZ 2, SET IN A CONCRETE MONUMENT, THE TOP OF WHICH IS FLUSH WITH THE GROUND, NORTHING 537,410.26, EASTING 6657,571.88. STATION 54AF, A U.S.C. AND G.S. AND STATE SURVEY DISK, STAMPED "54AF-213.30" SET IN AN OUTCROPPING LEDGE NORTHING 527,909.30 EASTING 657,003.70

TEMPORARY BENCHMARK CHART:

TBM #	DESCRIPTION	ELEV.
1	BRASS DISK RAY-AZ2 FOUND FLUSH IN CONCRETE PAD	126.71
2	TOP OF 6"x6" CONCRETE BOUND WITH LEAD PLUG FND 0.3' ABOVE GRADE	123.84

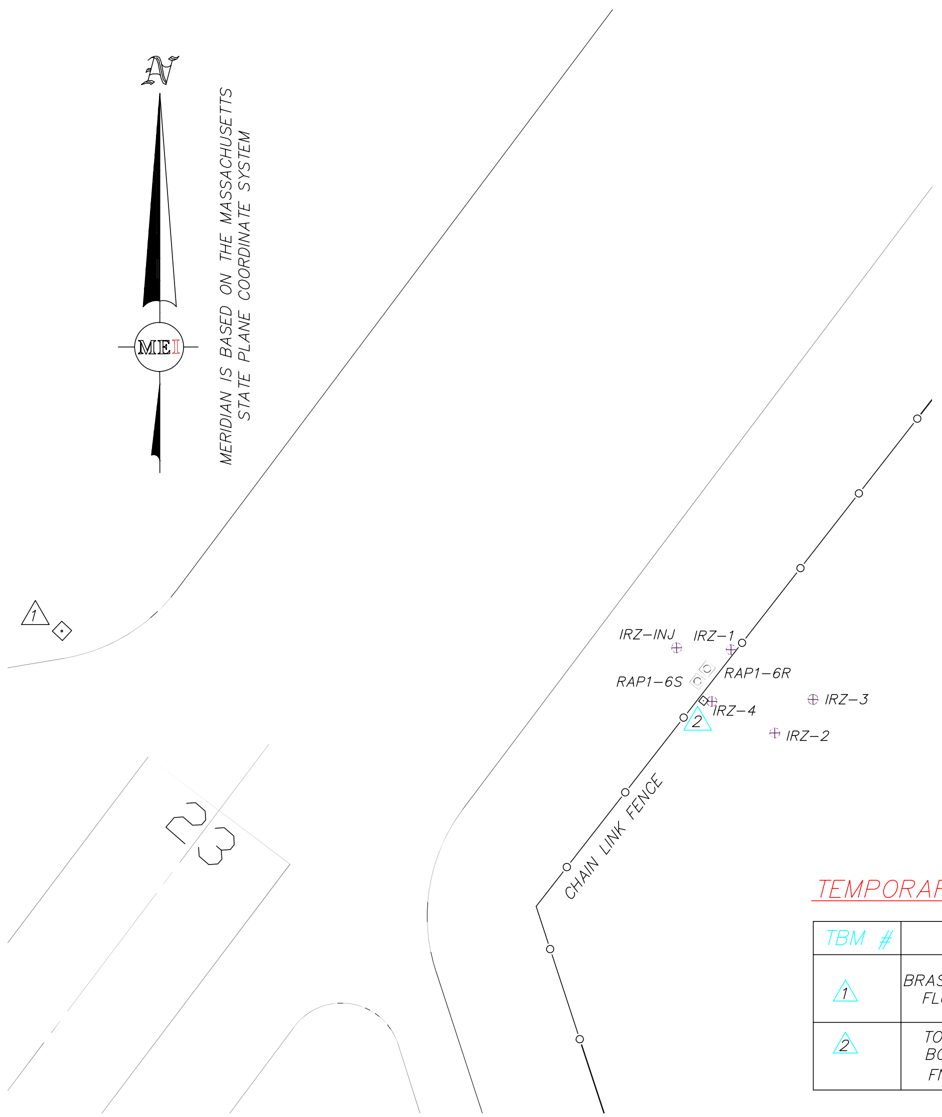
SKETCH PLAN
LOCATED IN
HANSCOM AIR FORCE BASE
(MIDDLESEX COUNTY)
PREPARED FOR
ARCADIS GERAGHTY & MILLER, INC.

SCALE: 1"=100' DATE: MAY 14, 2001

50 0 50 100 200

MERIDIAN
ENGINEERING, INC.
98 HIGH STREET
DANVERS, MASSACHUSETTS 01923
TELEPHONE: (978) 739-9130

DWG No. 3663WELLS_REV BK. 162G, PG. 26



LEGEND:

⊕ OBSERVATION WELL LOCATED BY MERIDIAN ENGINEERING, INC.

⊡ OBSERVATION WELL PREVIOUSLY LOCATED

NOTES:

1. THE SOLE PURPOSE OF THIS PLAN IS TO DEPICT THE LOCATION OF OBSERVATION WELLS AS PROVIDED BY ARCADIS GERAGHTY & MILLER, INC. AND LOCATED BY MERIDIAN ENGINEERING, INC. THE LOCATION OF ALL OTHER FEATURES, SUCH AS BUILDINGS, ROADS, FENCES, ETC. IS FOR ILLUSTRATIVE PURPOSES ONLY AND HAS BEEN PROVIDED BY THE CIVIL ENGINEERING DEPARTMENT OF HANSCOM AIR FORCE BASE.
2. THE FIELD SURVEY TO LOCATE MONITORING WELLS WAS PERFORMED ON THE GROUND BY MERIDIAN ENGINEERING, INC. ON DECEMBER 1, 2000.
3. HORIZONTAL LOCATION OF THE MONITORING WELL ARE BASED UPON THE MASSACHUSETTS PLANE COORDINATE SYSTEM (1927 NORTH AMERICAN DATUM).
4. ELEVATIONS DEPICTED ARE BASED UPON THE NATIONAL GEODETIC DATUM (N.G.V.D.) OF 1929.
5. STARTING BENCHMARK STATION RAY, 1957 AZMUTH #2 ELEVATION = 126.99
   STARTING BENCHMARK STATION 54AD ELEVATION = 218.530
   STARTING BENCHMARK STATION ARP 1963 ELEVATION = 126.489
6. STARTING HORIZONTAL CONTROL STATION RAY, 1957–AZMUTH #2 A MASSACHUSETTS DEPARTMENT OF PUBLIC WORKS TRAVERSE DISK STAMPED "RAY, 1957 AZ 2, SET IN A CONCRETE MONUMENT, THE TOP OF WHICH IS FLUSH WITH THE GROUND, NORTHING 537,410.26, EASTING 6657,571.88. STATION 54AF, A U.S.C. AND G.S. AND STATE SURVEY DISK, STAMPED "54AF–213.30" SET IN AN OUTCROPPING LEDGE NORTHING 527,909.30 EASTING 657,003.70

TEMPORARY BENCHMARK CHART:

TBM #	DESCRIPTION	ELEV.
△1	BRASS DISK RAY–AZ2 FOUND FLUSH IN CONCRETE PAD	126.71
△2	TOP OF 6"x6" CONCRETE BOUND WITH LEAD PLUG FND 0.3' ABOVE GRADE	123.84

SKETCH PLAN

LOCATED IN

HANSCOM AIR FORCE BASE

(MIDDLESEX COUNTY)

PREPARED FOR

ARCADIS GERAGHTY & MILLER, INC.

SCALE: 1"=100' DATE: DECEMBER 11, 2000

50 0 50 100 200

MERIDIAN
ENGINEERING, INC.
98 HIGH STREET
DANVERS, MASSACHUSETTS 01923
TELEPHONE: (978) 739–9130

DWG No. 3663WELLS

BK. 162G, PG. 20

HANSCOM A.F.B. OBSERVATION WELLS
PREPARED FOR ARCADIS GERAGHTY & MILLER, INC.
INSTALLATION RESTORATION PROGRAM

DECEMBER 11, 2000

DESCRIPTION	NORTHING	EASTING	GROUND ELEVATION	TOP OF PVC (INNERCASING) ELEVATION
IRZ-1	537439.3	658094.9	123.4+/-	122.82
IRZ-2	537369.1	658131.7	125.7+/-	127.62
IRZ-3	537397.3	658164.0	125.2+/-	128.16
IRZ-4	537396.2	658076.9	123.0+/-	126.00
IRZ-INJ	537440.9	658048.9	124.0+/-	123.82

NOTES:

1. ELEVATIONS DEPICTED ARE BASED UPON THE NATIONAL GEODETIC VERTICAL DATUM (N.G.V.D.) OF 1929.

2. HORIZONTAL LOCATIONS OF THE WELLS ARE BASED UPON THE MASSACHUSETTS STATE PLANE COORDINATE SYSTEM (1927 NORTH AMERICAN DATUM).

3. THE FIELD SURVEY TO LOCATE THE WELLS WAS PERFORMED ON THE GROUND BY MERIDIAN ENGINEERING, INC. ON DECEMBER 1, 2000.

KED\eew\F:\--\3563\survey\Observation Wells (excel) N.B 162G, P. 20

Appendix A-6a

Additional Discussion of Data Quality

Appendix A-6a: Additional Discussion of Data Quality

Data Quality Assessment

Much of the assessment of the data has been necessarily presented as part of the overall discussion of the data in Section 4.3. However, some specific data quality matters will be discussed in this section.

CAH Data Assessment

As planned, a validation was performed on the critical data sets for technology verification – the CAH data from groundwater analyzed at the offsite laboratory (STL) from the 5 abbreviated and 3 full sampling rounds. These data were shown to be very reliable. Full details of this assessment are presented in individual data set validation memos compiled as Appendix A-6b. In addition, although it was not planned in the demonstration plan, numerous additional rounds of TCE and DCE analyses were provided courtesy of Tom Best of Hanscom AFB. These included samples collected on some occasions by the Base's contractor (Shaw/IT) and on other occasions by ARCADIS. The analyses were performed at Hanscom by IT. As discussed in Section 4.3 the data sets with and without the on-site data lead to virtually identical conclusions, suggesting that the two laboratories are in rough agreement. There were essentially no "missing values" in the CAH data set. However as discussed in Section 4.3.3.3.4 we were not able to provide an ideal upgradient well data set since the demonstration zone turned out to be in a source area and the area immediately upgradient of the injection well was under the runway out run.

As discussed in Section 4.3.3.3.5, the wells outside the reactive zone showed little or no evidence of biodegradation. This strengthens the conclusions that substrate availability is linked with improved biodegradation. Since these wells were above, below, upgradient and side gradient from the wells that showed clear evidence of biodegradation (IRZ-1 and RAP1-6T) this strengthens the conclusion that contaminant removal at those three wells was due to enhanced biodegradation rather than displacement or dilution.

Further, enhanced degradation rates were calculated as discussed in Section 4.3.3.5. They were shown to be substantially enhanced over the pretreatment rates at this site. These degradation rates were shown to be higher than typical natural attenuation results previously observed in the field at other sites. TCE degradation rates were shown to be in the range expected for enhanced in-situ bioremediation systems based on results at other sites.

Finally, the trends in CAH and dissolved gas concentrations observed at this site and discussed in Section 4.3 were consistent with theory and the literature (including data collected at other sites and in the laboratory). Specifically, TCE degradation occurred before and under less reducing conditions than DCE degradation. All of these factors suggest that the CAH data set is quite reliable.

Assessment of Other Portions of the Data Set

Some difficulties encountered in well installation were described in Section 3.5.7.1.1 and difficulties encountered during injections in Section 3.5.1. However, neither of these problems is expected to materially affect overall data quality.

Other problems that were encountered during various sampling rounds are discussed in detail in Appendix A-6c. Most of these problems occurred with the field data or the TOC/DOC data. In particular the high levels of organic carbon in the injection wells caused problems with field measurements. However, these parameters are used more for process operation and interpretation than to assess the effectiveness of the technology. Therefore, it was judged that these problems did not materially affect the overall demonstration results.

Appendix A-6b

Validation Memos

ORGANIC DATA SUMMARY

Validation of Method 8260B Analysis (VOC's)
Hanscom AFB, Bedford, Massachusetts

Analyses Performed by Severn Trent Laboratories

* SAMPLE DESCRIPTION

The following six groundwater samples and associated QC samples were collected at the Hanscom AFB site and submitted to Severn Trent Laboratories in Arvada, Colorado for analysis by USEPA Method 8260B.

STL Lot #: B0F170112

HAN-GW-B239-1
HAN-GW-RAP1-6S-1
HAN-GW-RAP1-6R-1
HAN-GW-IRZ-3-1
HAN-GW-IRZ-2-1
HAN-GW-IRZ-4-1
HAN-GW-FB-1

* FIELD SAMPLING

The sampling documentation was reviewed. The sampling date, team members, location, depth, technique and field preparation techniques were appropriate and properly documented. There were no notations in the field notes or sample custody forms of the pH of the sample. Method 8260B requires that HCl be added as a preservation to a pH<2. It was noted that HCl was added, but the volume or pH was not recorded.

* SAMPLE SHIPPING/RECEIVING

Samples were received by STL June 17, 2000. Sample custody forms were reviewed. The temperature of the as received samples was 40 C, but no notation of the pH or headspace conditions of the samples.

* HOLDING TIME COMPLIANCE

Samples were taken on June 16, 2000 (?), shipped and received by the laboratory on June 17, 2000 and prepared and analyzed on June 27, 2000. Method 8260B stipulates a maximum hold time of 14 days. All samples were analyzed within the 14 days hold time.

* GC/MS INSTRUMENT PERFORMANCE CHECK

Laboratory report contains BFB tune data for June 27, 2000, the date the samples were analyzed. All tune criteria specified in the Functional Guidelines were met.

* GC/MS CALIBRATION

The initial calibration was performed on May 15, 2000. Acceptance criteria established for initial calibration is that relative response factors should be greater than or equal to 0.05 and the percent relative standard deviation (%RSD) between calibration levels should be less than 30%. All compounds in the target list (Table 1) met acceptance criteria.

Continuing calibration check standards were analyzed on June 26 and 27, 2000. The acceptance criteria established for the CCC is that the percent difference between RRF from the initial calibration must be within 25% and the actual calculated RRF must be greater than or equal to 0.05. All compounds in the target list meet these criteria.

* METHOD BLANK

One method blank was analyzed with the batch on June 27, 2000. There were no compounds detected in the method blank.

* EQUIPMENT BLANK

The field crew submitted an equipment blank and a field blank to the laboratory for analysis. No compounds were detected on the equipment blank

* SURROGATE RECOVERY

Surrogate recoveries for the target compounds in the samples were all within established control limits.

* MATRIX SPIKE ANALYSIS

MSD recovery for matrix spike samples were within the recovery limit of 80 – 120%.

? LABORATORY CONTROL SPIKE

All laboratory control samples were within established control limits.

? INTERNAL STANDARDS

Internal standards acceptance criteria requires that area counts for internal standards be within a factor of 2 (–50% to +100%) of the area counts associated with the calibration standard and that the retention time be within 30 seconds of the associated calibration standard. All internal standard areas and retention times met these criteria for all samples.

? COMPOUND IDENTIFICATION AND QUANTITATION

Functional guideline criteria require that relative retention times of identified compounds agree within 0.06 units of the associated standard. All retention times of the identified compounds were within 0.06 units of the continuing calibration standard retention times. The guidelines also require that the sample mass spectra match the standard mass spectra. Mass spectra data for the continuing calibration standard was not included in the laboratory data, so these could not be compared. Library matches of a few compounds were reviewed and compound identifications appear to be valid.

Reported concentrations were verified by hand-calculating the results using raw data reports and RRF's reported by the laboratory in the continuing calibration report. Concentrations reported by the laboratory were reproduced and are valid. However, the equation shown on the raw laboratory reports for the calculation of concentrations is not clear. The value referred to as ***amt.*** in the equation actually represents several values (i.e., the peak area of the compound of interest multiplied by the amount of internal standard divided by the area of the internal standard multiplied by the relative response factor of the target compound). In addition, dilution factors shown on the raw reports are inconsistent with those reported formally. The reviewer believes that all concentrations were reported correctly in the analytical report prepared for ARCADIS, but there are areas on the raw data reports that could lead to some confusion when the data is audited.

FIELD DUPLICATE

No field duplicate in this lot.

OVERALL DATA ASSESSMENT

The Method 8260B data for Lot # B0F170112included in this report have been validated according to the criteria presented in the *National Functional Guidelines for Organic Data Review* and are valid.

Table 1. Compounds Target List

Carbon Tetrachloride
Chlorobenzene
chloroethane
2-chloroethyl vinyl ether
chloroform
chloromethane
1,2 dichlorobenzene
1,3 dichlorobenzene
1,4 dichlorobenzene
trans-1,4- dichloro-2-butene
dichlorodifluromethane
1,1-dichloroethane
1,2-dichloroethane
cis-1,2-dichloroethene
trans-1,2-dichloroethene
1,1-dichloroethene
1,2-dichloroethene(total)
1,2-dichloropropane
cis-1,3-dichloropropene
trans-1,3-dichloropropene
trichloroethene
1,1,1 trichloroethane
vinyl chloride
tetrachloroethane
methylene chloride

ARCADIS G&M, Inc.
4915 Prospectus Dr.
Suite F
Durham
North Carolina, 27713
Tel 919 544 4535
Fax 919 544 5690

MEMO

Subject:
Validation of Water Samples Collected at Hanscom AFB 11/6/00

Date:
4/15/02

From:
Dennis Tabor

Drafted by:

Department:

ARCADIS Project No.:
RN009900.0017.00001

To:
Chris Lutes

Copies:

Four samples were collected on November 6, 2000 at Hanscom AFB, Massachusetts. These samples and a trip blank were submitted on November 7, 2000 to Severn Trent Laboratories (STL) Tampa East Facility in Tampa, Florida for analysis. This validation covers the samples submitted for Volatile organics by United States Environmental Protection Agency (USEPA) Method SW-846 8260B. Other aliquots were analyzed for other parameters that were not discussed in this memo.

Validation of this data was performed following the quality assurance/quality control (QA/QC) criteria set forth in the "USEPA Contract Laboratory Program (CLP) National Functional Guidelines for Organic Data Review", revised in June 2001. Method 8260B has slightly different criteria for some parameters than the CLP. Therefore, when the criteria were different and the 8260B criteria were more stringent the 8260B criteria were used.

This project is focused on the chlorinated ethenes. Trichloroethene was the primary compound of interest.

It is the reviewer's opinion that the quality of the data was acceptable with the qualifiers discussed below.

Sample Delivery Group B0K070141

Volatile Organic Data

I Preservation

The samples arrived at the lab promptly and were within the temperature criteria. The samples pH were not recorded as checked although preservation was indicated on the COC. The samples were analyzed within the Acid-Preserved hold time criteria of 14 days.

II Gas Chromatography/ Mass Spectrometer (GC/MS) Instrument Performance Check

Bromofluorobenzene checks were done successfully on the Initial Calibration and Analysis days. 8260B criteria are more stringent that CLP and therefore the 8260B criteria were used. The criteria for ion 174 in the CLP guidelines is 50-120% of ion m/z 95. The 8260B criteria is “greater than” 50% and that 95 is the base peak. The 174 ion was at 110% of 95 and therefore 95 was not the base peak. Therefore this may (subject to interpretation) have failed the 8260B criteria but the reviewer does not believe it would adversely effect the data.

III Initial Calibration

All of the Chloroethenes and the Deuterated Monitoring Compounds (DMCs) had Response Factors above 0.05in the Initial Calibration (IC). The range was from 10 to 625 ng introduced to the column. Relative Standard Deviations (RSDs) were below 15% for the Chloroethenes and the DMCs.

IV Continuing Calibration

The Samples were run in the same 12 hour window as the IC and therefore would not have been required.

V Blanks

All blanks reported non-detect for all compounds of interest.

VI Deuterated Monitoring Compounds (DMCs)

All criteria were met for all samples. The DMC compounds were mixed with the internal standard compounds and spiked as one solution. This prevents the DMC solution from being used to check to see if the proper amount of internal standard solution was added. This is not specifically forbidden in 8260B but the method does speak in different areas about spiking 10µl of one and then later of spiking the other solution. The reviewer believes that separate spiking provides more and different information than when spiking in one solution.

VII Matrix Spike/ Matrix Spike Duplicates (MS/MSDs)

No matrix spikes were run with this batch.

VIII Regional QA/QC

Not Applicable

IX Internal Standards

All criteria were met using the first level of the IC to compare.

X Target Compound Identification

The very high concentration samples showed poor ratio comparison in the non-diluted run. The compounds saturated the detector. They were fine in the diluted runs.

XI Compound Quantitation and Reported Contract Required Quantitation Limits (CRQLs)

Reporting limits were fine for this project. The sample quantitation in the diluted runs had a gap in the quantitation ranges. The range of quantitation in the IC was 0.4 to 25µg/l; the 1:500 diluted runs had a range of 200 to 12500µg/l. This allows compounds to be over range in the initial run and under range in the diluted run. This may have been a known and accepted but is out of the reviewer's knowledge. The lab is to be commended for reporting all detected values in both the initial and diluted runs.

The lab appears to have had prior knowledge of which samples would require dilution or screened the samples. The dilutions were run immediately after the samples. The reviewer would have preferred to see the dilutions run prior to higher level samples and at least on blank after a high sample to show no carryover.

XII Tentatively Identified Compounds (TICs)

Not Applicable

XIII System Performance

No problems noted.

XIV Overall Assessment of Data

The data appears to be very good, with only minor problems (dilutions).

ARCADIS G&M, Inc.
4915 Prospectus Dr.
Suite F
Durham
North Carolina, 27713
Tel 919 544 4535
Fax 919 544 5690

MEMO

Subject:
Validation of Water Samples Collected at Hanscom AFB 11/7/00

Date:
4/12/02

From:
Dennis Tabor

Drafted by:

Department:

ARCADIS Project No.:
RN009900.0017.00001

To:
Chris Lutes

Copies:

Six samples were collected on November 7, 2000 at Hanscom AFB, Massachusetts. These samples and a trip blank were submitted on November 8, 2000 to Severn Trent Laboratories (STL) Tampa East Facility in Tampa, Florida for analysis. This validation covers the samples submitted for Volatile organics by United States Environmental Protection Agency (USEPA) Method SW-846 8260B. Other aliquots were analyzed for other parameters that were not discussed in this memo.

Validation of this data was performed following the quality assurance/quality control (QA/QC) criteria set forth in the “USEPA Contract Laboratory Program (CLP) National Functional Guidelines for Organic Data Review”, revised in June 2001. Method 8260B has slightly different criteria for some parameters than the CLP. Therefore, when the criteria were different and the 8260B criteria were more stringent the 8260B criteria were used.

This project is focused on the chlorinated ethenes. Trichloroethene was the primary compound of interest.

It is the reviewer’s opinion that the quality of the data was acceptable with the qualifiers discussed below.

Sample Delivery Group B0K090260

Volatile Organic Data

I Preservation

The samples arrived at the lab promptly and were within the temperature criteria. The samples pH were not recorded as checked although preservation was indicated on the COC. The samples were analyzed within the Acid-preserved hold time criteria of 14 days.

II Gas Chromatography/ Mass Spectrometer (GC/MS) Instrument Performance Check

Bromofluorobenzene checks were done successfully on the Initial Calibration and Analysis days. 8260B criteria are more stringent that CLP and therefore the 8260B criteria were used.

III Initial Calibration

All of the Chloroethenes and the Deuterated Monitoring Compounds (DMCs) had Response Factors above 0.05in the Initial Calibration (IC). The range was from 10 to 625 ng introduced to the column. Relative Standard Deviations (RSDs) were below 15% for the Chloroethenes and the DMCs.

IV Continuing Calibration

The Continuing Calibration (CC) was run in the 12-hour analysis window before any of the samples were analyzed. The CC had RFs above 0.05 for the Chloroethenes and the DMCs. The Relative Percent Deviations (RPDs) from the IC were below 15% for the Chloroethenes and the DMC

V Blanks

All blanks reported non-detect for all compounds of interest.

VI Deuterated Monitoring Compounds (DMCs)

All criteria were met for all samples.

VII Matrix Spike/ Matrix Spike Duplicates (MS/MSDs)

Criteria were met for the MS but one compound was one percent outside of criteria for one compound. Data quality would not be significantly affected.

VIII Regional QA/QC

Not Applicable

IX Internal Standards

All criteria were met using the first level of the IC to compare.

X Target Compound Identification

The very high concentration samples showed poor ratio comparison in the non-diluted run. The compounds saturated the detector. They were fine in the diluted runs.

XI Compound Quantitation and Reported Contract Required Quantitation Limits (CRQLs)

Reporting limits were fine for this project. The sample quantitation in the diluted runs had a gap in the quantitation ranges. The range of quantitation in the IC was 0.4 to 25µg/l; the diluted runs had a range of 200 to 12500µg/l. This allows compounds to be over range in the initial run and under range in the diluted run. This may have been a known and accepted but is out of the reviewer's knowledge. The lab is to be commended for reporting all detected values in both the initial and diluted runs.

The lab appears to have had prior knowledge of which samples would require dilution or screened the samples. The dilutions were run immediately after the samples. The reviewer would have preferred to see the dilutions run prior to higher level samples and at least on blank after a high sample to show no carryover.

XII Tentatively Identified Compounds (TICs)

Not Applicable

XIII System Performance

No problems noted.

XIV Overall Assessment of Data

The data appears to be very good, with only minor problems (MSD and dilutions).

ARCADIS

ARCADIS G&M, Inc.
4915 Prospectus Dr.
Suite F
Durham
North Carolina, 27713
Tel 919 544 4535
Fax 919 544 5690

MEMO

Subject:
Validation of Water Samples Collected at Hanscom AFB 4/05-06/2001

Date:
4/16/02

From:
Dennis Tabor

Drafted by:

Department:

ARCADIS Project No.:
RN009900.0017.00001

To:
Chris Lutes

Copies:

Ten samples were collected on April 5 and 6, 2001 at Hanscom AFB, Massachusetts. These samples and a trip blank were submitted on April 7, 2001 to Severn Trent Laboratories (STL) Tampa East Facility in Tampa, Florida for analysis. This validation covers the samples submitted for Volatile organics by United States Environmental Protection Agency (USEPA) Method SW-846 8260B. Other aliquots were analyzed for other parameters that were not discussed in this memo.

Validation of this data was performed following the quality assurance/quality control (QA/QC) criteria set forth in the "USEPA Contract Laboratory Program (CLP) National Functional Guidelines for Organic Data Review", revised in June 2001. Method 8260B has slightly different criteria for some parameters than the CLP. Therefore, when the criteria were different and the 8260B criteria were more stringent the 8260B criteria were used.

This project is focused on the chlorinated ethenes. Trichloroethene was the primary compound of interest. Acetone and other ketones were of secondary interest.

It is the reviewer's opinion that the quality of the data was acceptable with the qualifiers discussed below, for all samples except HAN-GW-IRZ-INJ. The differences between the diluted and undiluted values are more than are expected therefore the higher value should be used.

Sample Delivery Group B1D090101

Volatile Organic Data

I Preservation

The samples arrived at the lab promptly and were within the temperature criteria. The samples pH were indicated as checked at the lab. Preservation was indicated on the Chain-of-Custody (COC) for three of the ten samples. The samples were analyzed within the Acid-preserved hold time criteria of 14 days. The trip blank was not on the COC. It is assumed that the lab made contact with the project personnel to get direction for the trip blank and two samples which had no analysis requested on the COC.

II Gas Chromatography/ Mass Spectrometer (GC/MS) Instrument Performance Check

Bromofluorobenzene checks were done successfully on the Initial Calibration and Analysis days. 8260B criteria are more stringent that CLP and therefore the 8260B criteria were used.

III Initial Calibration

All of the Chloroethenes and the Deuterated Monitoring Compounds (DMCs) had Response Factors above 0.05in the Initial Calibration (IC). The range was from 25 to 625 ng introduced to the column. Relative Standard Deviations (RSDs) were below 15% for the Chloroethenes and the DMCs. The light ketones were low on response factor and too high in variability. The Ketone data should not be used for precise quantitation.

IV Continuing Calibration

The Continuing Calibration (CC) was run in the 12-hour analysis window before any of the samples were analyzed. The CC had RFs above 0.05 for the Chloroethenes and the DMCs. The Relative Percent Deviations (RPDs) from the IC were below 15% for the Chloroethenes and the DMC. The ketones were also low on response factor and high on variability in the CC.

V Blanks

All blanks reported non-detect for all compounds of interest.

VI Deuterated Monitoring Compounds (DMCs)

All criteria were met for all samples.

VII Matrix Spike/ Matrix Spike Duplicates (MS/MSDs)

MS/MSD appeared in the run log but was not reported or mentioned anywhere else in the report. This is of high concern. It may be that the MS/MSD was not requested and the analyst accidentally ran it, but if so the lab would have avoided a suspicion by reporting it anyway.

The laboratory control spikes indicate that the ketones should not be used for precise quantitation. Order of magnitude or detect/nondetect decisions could be supported.

VIII Regional QA/QC

Not Applicable

IX Internal Standards

All criteria were met.

X Target Compound Identification

The very high concentration samples showed poor ratio comparison in the non-diluted run. The compounds saturated the detector. They were fine in the diluted runs. The reference spectrum for 1,2-Dichloroethane includes the 78 ion for the co-eluting benzene. The ions for styrene are in the reference spectrum for o-xylene. The ions for butylbenzene are in the reference spectrum for 1,2-dichlorobenzene. This many extra peaks in reference spectra indicate that the reference spectra were taken from a mix of compounds and the reference spectra for the co-eluting compounds have not been removed. This could be a problem leading to misidentification. These were not compounds of interest for this project and therefore the reviewer does not see a problem. But these compounds were detected and if the data is used for tertiary purposes at a later time it could be a problem. No misidentifications were noticed.

XI Compound Quantitation and Reported Contract Required Quantitation Limits (CRQLs)

Reporting limits were fine for this project. The sample quantitation in the diluted runs had a gap in the quantitation ranges. The range of quantitation in the IC was 1 to 25µg/l; the 500X diluted runs had a range of 500 to 12500µg/l. This allows compounds to be over range in the initial run and under range in the diluted run. This occurred for at least one compound of interest in each run that required high dilution (7 of the 8 diluted samples). In one sample an overrange was diluted to a non-detect. This may have been a known and accepted but is out of the reviewer’s knowledge. The lab is to be commended for reporting all detected values in both the initial and diluted runs.

The lab appears to have had prior knowledge of which samples would require dilution or screened the samples. The dilutions were run immediately after the samples. The reviewer would have preferred to see the dilutions run prior to higher level samples and at least one blank after a high sample to show no carryover.

One sample had very poor agreement between the diluted and undiluted runs. HAN-GW-IRZ-INJ seemed to have more difference than had been noted in other samples.

XII Tentatively Identified Compounds (TICs)

Not Applicable

XIII System Performance

No problems noted.

XIV Overall Assessment of Data

The data appears to be very good, with only minor problems (MS/MSD, reference sprectra and dilutions).

ARCADIS G&M, Inc.
4915 Prospectus Dr.
Suite F
Durham
North Carolina, 27713
Tel 919 544 4535
Fax 919 544 5690

MEMO

Subject:
Validation of Water Samples Collected at Hanscom AFB 5/3/2001

Date:
7/26/02

From:
Dennis Tabor

Drafted by:

Department:

ARCADIS Project No.:
RN009900.0017.00001

To:
Chris Lutes

Copies:

Two samples were collected on May 3, 2001 at Hanscom AFB, Massachusetts. These samples and a trip blank were submitted on May 4, 2001 to Severn Trent Laboratories (STL) Tampa East Facility in Tampa, Florida for analysis. This validation covers the samples submitted for Volatile organics by United States Environmental Protection Agency (USEPA) Method SW-846 8260B. Other aliquots were analyzed for other parameters that were not discussed in this memo.

Validation of this data was performed following the quality assurance/quality control (QA/QC) criteria set forth in the "USEPA Contract Laboratory Program (CLP) National Functional Guidelines for Organic Data Review", revised in June 2001. Method 8260B has slightly different criteria for some parameters than the CLP. Therefore, when the criteria were different and the 8260B criteria were more stringent the 8260B criteria were used.

This project is focused on the chlorinated ethenes. Trichloroethene was the primary compound of interest. Acetone and other ketones were of secondary interest.

It is the reviewer's opinion that the quality of the data was acceptable with the qualifiers discussed below, for all samples.

Sample Delivery Group B1E040122

Volatile Organic Data

I Preservation

The samples arrived at the lab promptly and were within the temperature criteria. The samples pH were indicated as checked by the analyst using the footnote “All aqueous samples had a pH < 2 unless otherwise noted” the reviewer feels an actual entry indicating the pH would be a more comforting indicator that it was actually checked. Preservation was indicated on the Chain-of-Custody (COC) for the five samples. The samples were analyzed within the Acid-preserved hold time criteria of 14 days. The trip blanks ware not on the COC. The lab made contact with the project personnel to get direction for the trip blank it was analyzed with this set of samples.

II Gas Chromatography/ Mass Spectrometer (GC/MS) Instrument Performance Check

Bromofluorobenzene checks were done successfully on the Initial Calibration and Analysis days. 8260B criteria are more stringent that CLP and therefore the 8260B criteria were used.

III Initial Calibration

All of the Chloroethenes and the Deuterated Monitoring Compounds (DMCs) had Response Factors above 0.05in the Initial Calibration (IC). The range was from 25 to 625 ng introduced to the column. Relative Standard Deviations (RSDs) were below 15% for the Chloroethenes and the DMCs. The ketones were low on response factor and too high in variability. The Ketone data should not be used for precise quantitation.

IV Continuing Calibration

The ICAL and Samples were run in the same 12 hr window. No CCC was needed but the midpoint of the curve was treated as a CCC and was already discussed.

V Blanks

All blanks reported non-detect for all compounds of interest.

VI Deuterated Monitoring Compounds (DMCs)

All criteria were met for all samples.

VII Matrix Spike/ Matrix Spike Duplicates (MS/MSDs)

MS/MSD appeared in the run log in the batch but was not project specific and therefore only the summary sheet is in the report. It looked fine.

The laboratory control spikes were well reported and were acceptable.

VIII Regional QA/QC

Not Applicable

IX Internal Standards

All criteria were met.

X Target Compound Identification

The very high concentration samples showed poor ratio comparison in the non-diluted run. The compounds saturated the detector. They were fine in the diluted runs. The reference spectrum for 1,2-Dichloroethane includes the 78 ion for the co-eluting benzene. The ions for styrene are in the reference spectrum for o-xylene. The ions for butylbenzene are in the reference spectrum for 1,2-dichlorobenzene. This many extra peaks in reference spectra indicate that the reference spectra were taken from a mix of compounds and the reference spectra for the co-eluting compounds have not been removed. This could be a problem leading to misidentification. These were not compounds of interest for this project and therefore the reviewer does not see a problem. But these compounds were detected and if the data is used for tertiary purposes at a later time it could be a problem. No mis-identifications were noticed.

XI Compound Quantitation and Reported Contract Required Quantitation Limits (CRQLs)

Reporting limits were fine for this project. The sample quantitation in the diluted runs had a gap in the quantitation ranges. The range of quantitation in the IC was 1 to 25µg/l; the 200X diluted runs had a range of 200 to 5000µg/l. This allows compounds to be over range in the initial run and under range in the diluted run. This occurred for at least one compound of interest in each run that required high dilution. This may have been a known and accepted but is out of the reviewer's knowledge. The lab is to be commended for reporting all detected values in both the initial and diluted runs.

The lab appears to have had prior knowledge of which samples would require dilution or screened the samples. The dilutions were run immediately after the samples. The reviewer would have preferred to see the dilutions run prior to higher level samples and at least one blank after a high sample to show no carryover.

XII Tentatively Identified Compounds (TICs)

Not Applicable

XIII System Performance

No problems noted.

XIV Overall Assessment of Data

The data appears to be very good, with only minor problems (reference spectra and dilutions).

ARCADIS G&M, Inc.
4915 Prospectus Dr.
Suite F
Durham
North Carolina, 27713
Tel 919 544 4535
Fax 919 544 5690

MEMO

Subject:
Validation of Water Samples Collected at Hanscom AFB 5/4/2001

Date:
7/26/02

From:
Dennis Tabor

Drafted by:

Department:

ARCADIS Project No.:
RN009900.0017.00001

To:
Chris Lutes

Copies:

Five samples were collected on May 4, 2001 at Hanscom AFB, Massachusetts. These samples and trip blanks were submitted on May 5, 2001 to Severn Trent Laboratories (STL) Tampa East Facility in Tampa, Florida for analysis. This validation covers the samples submitted for Volatile organics by United States Environmental Protection Agency (USEPA) Method SW-846 8260B. Other aliquots were analyzed for other parameters that were not discussed in this memo.

Validation of this data was performed following the quality assurance/quality control (QA/QC) criteria set forth in the "USEPA Contract Laboratory Program (CLP) National Functional Guidelines for Organic Data Review", revised in June 2001. Method 8260B has slightly different criteria for some parameters than the CLP. Therefore, when the criteria were different and the 8260B criteria were more stringent the 8260B criteria were used.

This project is focused on the chlorinated ethenes. Trichloroethene was the primary compound of interest. Acetone and other ketones were of secondary interest.

It is the reviewer's opinion that the quality of the data was acceptable with the qualifiers discussed below, for all samples.

Sample Delivery Group B1E050110

Volatile Organic Data

I Preservation

The samples arrived at the lab promptly and were within the temperature criteria. The samples pH were indicated as checked by the analyst using the footnote "All aqueous samples had a pH < 2 unless otherwise noted" the reviewer feels an actual entry indicating the pH would be a more comforting indicator that it was actually checked. Preservation was not indicated on the Chain-of-Custody (COC) for the five samples. The samples were analyzed within the Acid-preserved hold time criteria of 14 days. The trip blanks ware not on the COC. The lab made contact with the project personnel to get direction for the trip blank it was not to be analyzed with this set of samples.

II Gas Chromatography/ Mass Spectrometer (GC/MS) Instrument Performance Check

Bromofluorobenzene checks were done successfully on the Initial Calibration and Analysis days. 8260B criteria are more stringent that CLP and therefore the 8260B criteria were used.

III Initial Calibration

All of the Chloroethenes and the Deuterated Monitoring Compounds (DMCs) had Response Factors above 0.05in the Initial Calibration (IC). The range was from 25 to 625 ng introduced to the column. Relative Standard Deviations (RSDs) were below 15% for the Chloroethenes and the DMCs. The ketones were low on response factor and too high in variability. The Ketone data should not be used for precise quantitation.

IV Continuing Calibration

The ICAL and Samples were run in the same 12 hr window. No CCC was needed but the midpoint of the curve was treated as a CCC and was already discussed.

V Blanks

All blanks reported non-detect for all compounds of interest.

VI Deuterated Monitoring Compounds (DMCs)

All criteria were met for all samples.

VII Matrix Spike/ Matrix Spike Duplicates (MS/MSDs)

MS/MSD appeared in the run log in the batch but was project specific. It looked fine.

The laboratory control spikes were well reported and were acceptable.

VIII Regional QA/QC

Not Applicable

IX Internal Standards

All criteria were met.

X Target Compound Identification

The very high concentration samples showed poor ratio comparison in the non-diluted run. The compounds saturated the detector. They were fine in the diluted runs. The reference spectrum for 1,2-Dichloroethane includes the 78 ion for the co-eluting benzene. The ions for styrene are in the reference spectrum for o-xylene. The ions for butylbenzene are in the reference spectrum for 1,2-dichlorobenzene. This many extra peaks in reference spectra indicate that the reference spectra were taken from a mix of compounds and the reference spectra for the co-eluting compounds have not been removed. This could be a problem leading to misidentification. These were not compounds of interest for this project and therefore the reviewer does not see a problem. But these compounds were detected and if the data is used for tertiary purposes at a later time it could be a problem. No mis-identifications were noticed.

XI Compound Quantitation and Reported Contract Required Quantitation Limits (CRQLs)

Reporting limits were fine for this project. The sample quantitation in the diluted runs had a gap in the quantitation ranges. The range of quantitation in the IC was 1 to 25µg/l; the 500X diluted runs had a range of 500 to 12500µg/l. This allows compounds to be over range in the initial run and under range in the diluted run. This occurred for at least one compound of interest in each run that required high dilution. This may have been a known and accepted but is out of the reviewer's knowledge. The lab is to be commended for reporting all detected values in both the initial and diluted runs.

The lab appears to have had prior knowledge of which samples would require dilution or screened the samples. The dilutions were run immediately after the samples. The reviewer would have preferred to see the dilutions run prior to higher level samples and at least one blank after a high sample to show no carryover.

XII Tentatively Identified Compounds (TICs)

Not Applicable

XIII System Performance

No problems noted.

XIV Overall Assessment of Data

The data appears to be very good, with only minor problems (reference spectra and dilutions).

ARCADIS G&M, Inc.
4915 Prospectus Dr.
Suite F
Durham
North Carolina, 27713
Tel 919 544 4535
Fax 919 544 5690

MEMO

Subject:
Validation of Water Samples Collected at Hanscom AFB 5/7/2001

Date:
5/6/02

From:
Dennis Tabor

Drafted by:

Department:

ARCADIS Project No.:
RN009900.0017.00001

To:
Chris Lutes

Copies:

Three samples were collected on May 7, 2001 at Hanscom AFB, Massachusetts. These samples and a trip blank were submitted on May 8, 2001 to Severn Trent Laboratories (STL) Tampa East Facility in Tampa, Florida for analysis. This validation covers the samples submitted for Volatile organics by United States Environmental Protection Agency (USEPA) Method SW-846 8260B. Other aliquots were analyzed for other parameters that were not discussed in this memo.

Validation of this data was performed following the quality assurance/quality control (QA/QC) criteria set forth in the “USEPA Contract Laboratory Program (CLP) National Functional Guidelines for Organic Data Review”, revised in June 2001. Method 8260B has slightly different criteria for some parameters than the CLP. Therefore, when the criteria were different and the 8260B criteria were more stringent the 8260B criteria were used.

This project is focused on the chlorinated ethenes. Trichloroethene was the primary compound of interest. Acetone and other ketones were of secondary interest.

It is the reviewer’s opinion that the quality of the data was acceptable with the qualifiers discussed below, for all samples.

Sample Delivery Group B1E080187

Volatile Organic Data

I Preservation

The samples arrived at the lab promptly and were within the temperature criteria. The samples pH were indicated as checked by the analyst using the footnote "All aqueous samples had a pH < 2 unless otherwise noted" the reviewer feels an actual entry indicating the pH would be a more comforting indicator that it was actually checked. Preservation was indicated on the Chain-of-Custody (COC) for the three samples. The samples were analyzed within the Acid-preserved hold time criteria of 14 days. The trip blank was not on the COC. It is assumed that the lab made contact with the project personnel to get direction for the trip blank.

II Gas Chromatography/ Mass Spectrometer (GC/MS) Instrument Performance Check

Bromofluorobenzene checks were done successfully on the Initial Calibrations and Analysis days. 8260B criteria are more stringent that CLP and therefore the 8260B criteria were used.

III Initial Calibration

All of the Chloroethenes and the Deuterated Monitoring Compounds (DMCs) had Response Factors above 0.05in the Initial Calibration (IC). The range was from 25 to 625 ng introduced to the column. Relative Standard Deviations (RSDs) were below 15% for the Chloroethenes and the DMCs. The ketones were low on response factor and too high in variability. The Ketone data should not be used for precise quantitation.

IV Continuing Calibration

The Continuing Calibration (CC) was run in the 12-hour analysis window before any of the samples were analyzed. The CC had RFs above 0.05 for the Chloroethenes and the DMCs. The Relative Percent Deviations (RPDs) from the IC were below 15% for the Chloroethenes and the DMC. The ketones were also low on response factor and high on variability in the CC.

V Blanks

All blanks reported non-detect for all compounds of interest.

VI Deuterated Monitoring Compounds (DMCs)

All criteria were met for all samples, except one Dibromofluoromethane in one undiluted run. Due to the remoteness of this DMC to the compounds of interest, this one “out” is of no concern.

VII Matrix Spike/ Matrix Spike Duplicates (MS/MSDs)

MS/MSD appeared in the run log in the batch but was not project specific and therefore only the summary sheet is in the report. It looked fine.

The laboratory control spikes were well reported and were acceptable.

VIII Regional QA/QC

Not Applicable

IX Internal Standards

All criteria were met.

X Target Compound Identification

The very high concentration samples showed poor ratio comparison in the non-diluted run. The compounds saturated the detector. They were fine in the diluted runs. The reference spectrum for 1,2-Dichloroethane includes the 78 ion for the co-eluting benzene. The ions for styrene are in the reference spectrum for o-xylene. The ions for butylbenzene are in the reference spectrum for 1,2-dichlorobenzene. This many extra peaks in reference spectra indicate that the reference spectra were taken from a mix of compounds and the reference spectra for the co-eluting compounds have not been removed. This could be a problem leading to misidentification. These were not compounds of interest for this project and therefore the reviewer does not see a problem. But these compounds were detected and if the data is used for tertiary purposes at a later time it could be a problem. No mis-identifications were noticed.

XI Compound Quantitation and Reported Contract Required Quantitation Limits (CRQLs)

Reporting limits were fine for this project. The sample quantitation in the diluted runs had a gap in the quantitation ranges. The range of quantitation in the IC was 1 to 25µg/l; the 500X diluted runs had a range of 500 to 12500µg/l. This allows compounds to be over range in the initial run and under range in the diluted run. This occurred for at least one compound of interest in each run that required high dilution. In one sample an overrange was diluted to a non-detect. This may have been a known and accepted but is out of the reviewer's knowledge. The lab is to be commended for reporting all detected values in both the initial and diluted runs.

The lab appears to have had prior knowledge of which samples would require dilution or screened the samples. The dilutions were run immediately after the samples. The reviewer would have preferred to see the dilutions run prior to higher level samples and at least one blank after a high sample to show no carryover.

XII Tentatively Identified Compounds (TICs)

Not Applicable

XIII System Performance

No problems noted.

XIV Overall Assessment of Data

The data appears to be very good, with only minor problems (reference spectra and dilutions).

ARCADIS G&M, Inc.
4915 Prospectus Dr.
Suite F
Durham
North Carolina, 27713
Tel 919 544 4535
Fax 919 544 5690

MEMO

Subject:
Validation of Water Samples Collected at Hanscom AFB 5/8/2001

Date:
6/17/02

From:
Dennis Tabor

Drafted by:

Department:

ARCADIS Project No.:
RN009900.0017.00001

To:
Chris Lutes

Copies:

Two samples were collected on May 8, 2001 at Hanscom AFB, Massachusetts. These samples and two trip blanks were submitted on May 9, 2001 to Severn Trent Laboratories (STL) Tampa East Facility in Tampa, Florida for analysis. This validation covers the samples submitted for Volatile organics by United States Environmental Protection Agency (USEPA) Method SW-846 8260B. Other aliquots were analyzed for other parameters that were not discussed in this memo.

Validation of this data was performed following the quality assurance/quality control (QA/QC) criteria set forth in the "USEPA Contract Laboratory Program (CLP) National Functional Guidelines for Organic Data Review", revised in June 2001. Method 8260B has slightly different criteria for some parameters than the CLP. Therefore, when the criteria were different and the 8260B criteria were more stringent the 8260B criteria were used.

This project is focused on the chlorinated ethenes. Trichloroethene was the primary compound of interest. Acetone and other ketones were of secondary interest.

It is the reviewer's opinion that the quality of the data was acceptable with the qualifiers discussed below, for all samples.

Sample Delivery Group B1E090142

Volatile Organic Data

I Preservation

The samples arrived at the lab promptly and were within the temperature criteria. The samples pH were indicated as checked by the analyst using the footnote "All aqueous samples had a pH < 2 unless otherwise noted" the reviewer feels an actual entry indicating the pH would be a more comforting indicator that it was actually checked. Preservation was indicated on the Chain-of-Custody (COC) for the three samples. The samples were analyzed within the Acid-preserved hold time criteria of 14 days. The trip blanks were not on the COC. The lab contacted the project leader and they were not analyzed.

II Gas Chromatography/ Mass Spectrometer (GC/MS) Instrument Performance Check

Bromofluorobenzene checks were done successfully on the Initial Calibrations and Analysis days. 8260B criteria are more stringent that CLP and therefore the 8260B criteria were used.

III Initial Calibration

All of the Chloroethenes and the Deuterated Monitoring Compounds (DMCs) had Response Factors above 0.05in the Initial Calibration (IC). The range was from 25 to 625 ng introduced to the column. Relative Standard Deviations (RSDs) were below 15% for the Chloroethenes and the DMCs. Acetone was low on response factor and too high in variability.

IV Continuing Calibration

The Continuing Calibration (CC) was run in the 12-hour analysis window before any of the samples were analyzed. The CC had RFs above 0.05 for the Chloroethenes and the DMCs. The Relative Percent Deviations (RPDs) from the IC were below 15% for the Chloroethenes and the DMC. The ketones were also low on response factor in the CC.

V Blanks

All blanks reported non-detect for all compounds of interest.

VI Deuterated Monitoring Compounds (DMCs)

All criteria were met for all samples. The listed criteria are not 8260B or CLP and are wider than either. The lab should note in the case narrative if in-house criteria are being used instead of method listed criteria.

VII Matrix Spike/ Matrix Spike Duplicates (MS/MSDs)

MS/MSD appeared in the run log in the batch but was not project specific and therefore only the summary sheet is in the report. 1,1-Dichloroethene was out on one of the seven spiked samples. Trichloroethene was in range and looked good for all spiked samples.

The laboratory control spikes were well reported and were acceptable.

VIII Regional QA/QC

Not Applicable

IX Internal Standards

All criteria were met.

X Target Compound Identification

The reference spectrum for 1,2-Dichloroethane includes the 78 ion for the co-eluting benzene. The ions for styrene are in the reference spectrum for o-xylene. The ions for butylbenzene are in the reference spectrum for 1,2-dichlorobenzene. This many extra peaks in reference spectra indicate that the reference spectra were taken from a mix of compounds and the reference spectra for the co-eluting compounds have not been removed. This could be a problem leading to misidentification. These were not compounds of interest for this project and therefore the reviewer does not see a problem. But these compounds were detected and if the data is used for tertiary purposes at a later time it could be a problem. No mis-identifications were noticed.

XI Compound Quantitation and Reported Contract Required Quantitation Limits (CRQLs)

Reporting limits were fine for this project. The sample quantitation in the diluted runs had a gap in the quantitation ranges. The range of quantitation in the IC was 1 to 25µg/l; the 500X diluted runs had a range of 500 to 12500µg/l. This allows compounds to be over range in the initial run and under range in the diluted run. This may have been a known and accepted but is out of the reviewer's knowledge. The lab is to be commended for reporting all detected values in both the initial and diluted runs.

The lab appears to have had prior knowledge of which samples would require dilution or screened the samples. The dilutions were run immediately after the samples. The reviewer would have preferred to see the dilutions run prior to higher level samples and at least one blank after a high sample to show no carryover.

XII Tentatively Identified Compounds (TICs)

Not Applicable

XIII System Performance

No problems noted.

XIV Overall Assessment of Data

The data appears to be very good, with only minor problems (reference spectra and dilutions).

ARCADIS G&M, Inc.
4915 Prospectus Dr.
Suite F
Durham
North Carolina, 27713
Tel 919 544 4535
Fax 919 544 5690

MEMO

Subject:
Validation of Water Samples Collected at Hanscom AFB 7/11-12/2001

Date:
5/6/02

From:
Dennis Tabor

Drafted by:

Department:

ARCADIS Project No.:
RN009900.0017.00001

To:
Chris Lutes

Copies:

Eleven samples were collected on July 11and 12, 2001 at Hanscom AFB, Massachusetts. These samples were submitted on July 13, 2001 to Severn Trent Laboratories (STL) Tampa East Facility in Tampa, Florida for analysis. This validation covers the samples submitted for Volatile organics by United States Environmental Protection Agency (USEPA) Method SW-846 8260B. Other aliquots were analyzed for other parameters that were not discussed in this memo.

Validation of this data was performed following the quality assurance/quality control (QA/QC) criteria set forth in the "USEPA Contract Laboratory Program (CLP) National Functional Guidelines for Organic Data Review", revised in June 2001. Method 8260B has slightly different criteria for some parameters than the CLP. Therefore, when the criteria were different and the 8260B criteria were more stringent the 8260B criteria were used.

This project is focused on the chlorinated ethenes. Trichloroethene was the primary compound of interest. Acetone and other ketones were of secondary interest.

It is the reviewer's opinion that the quality of the data was acceptable with the qualifiers discussed below, for all samples.

Sample Delivery Group B1G130213

Volatile Organic Data

I Preservation

The samples arrived at the lab promptly and were within the temperature criteria. The samples pH were indicated as checked by the analyst using the footnote "All aqueous samples had a pH < 2 unless otherwise noted" the reviewer feels an actual entry indicating the pH would be a more comforting indicator that it was actually checked. Preservation was indicated on the Chain-of-Custody (COC) for all the samples. The samples were analyzed within the Acid-preserved hold time criteria of 14 days. Sample HANGW-IRZ-INJ had air bubbles in the sample collection vials. This could adversely affect the data.

II Gas Chromatography/ Mass Spectrometer (GC/MS) Instrument Performance Check

Bromofluorobenzene checks were done successfully on the Initial Calibrations and Analysis days. 8260B criteria are more stringent that CLP and therefore the 8260B criteria were used.

III Initial Calibration

All of the Chloroethenes and the Deuterated Monitoring Compounds (DMCs) had Response Factors above 0.05in the Initial Calibration (IC). The range was from 25 to 625 ng introduced to the column. Relative Standard Deviations (RSDs) were below 15% for the Chloroethenes and the DMCs. The ketones were low on response factor and too high in variability. The Ketone data should not be used for precise quantitation.

IV Continuing Calibration

The Continuing Calibration (CC) was run in the 12-hour analysis window before any of the samples were analyzed. The CC had RFs above 0.05 for the Chloroethenes and the DMCs. The Relative Percent Deviations (RPDs) from the IC were below 15% for the Chloroethenes and the DMC. The ketones were also low on response factor and high on variability in the CC.

V Blanks

All blanks reported non-detect for all compounds of interest.

VI Deuterated Monitoring Compounds (DMCs)

All criteria were met for all samples. The specified criteria on the reports is neither CLP nor 8260B. The recoveries look fine but if in-house recovery limits are being used it should be noted in the case narrative.

VII Matrix Spike/ Matrix Spike Duplicates (MS/MSDs)

MS/MSD appeared in the run log in the batch but was project specific. It looked fine. The trichloroethene was unusable because of the high levels in the native samples.

The laboratory control spikes were well reported and were acceptable.

VIII Regional QA/QC

Not Applicable

IX Internal Standards

All criteria were met.

X Target Compound Identification

The very high concentration samples showed poor ratio comparison in the non-diluted run. The compounds saturated the detector. They were fine in the diluted runs. The reference spectrum for 1,2-Dichloroethane includes the 78 ion for the co-eluting benzene. The ions for styrene are in the reference spectrum for o-xylene. The ions for butylbenzene are in the reference spectrum for 1,2-dichlorobenzene. This many extra peaks in reference spectra indicate that the reference spectra were taken from a mix of compounds and the reference spectra for the co-eluting compounds have not been removed. This could be a problem leading to misidentification. These were not compounds of interest for this project and therefore the reviewer does not see a problem. But these compounds were detected and if the data is used for tertiary purposes at a later time it could be a problem. No mis-identifications were noticed.

XI Compound Quantitation and Reported Contract Required Quantitation Limits (CRQLs)

Reporting limits were fine for this project. The sample quantitation in the diluted runs had a gap in the quantitation ranges. The range of quantitation in the IC was 1 to 25μg/l; the 500X diluted runs had a range of 500 to 12500μg/l. This allows compounds to be over range in the initial run and under range in the diluted run. This occurred for at least one compound of interest in each run that required high dilution. This may have been a known and accepted but is out of the reviewer's knowledge. The lab is to be commended for reporting all detected values in both the initial and diluted runs.

The lab appears to have had prior knowledge of which samples would require dilution or screened the samples. The dilutions were run immediately after the samples. The reviewer would have preferred to see the dilutions run prior to higher level samples and at least one blank after a high sample to show no carryover.

XII Tentatively Identified Compounds (TICs)

Not Applicable

XIII System Performance

No problems noted.

XIV Overall Assessment of Data

The data appears to be very good, with only minor problems (reference spectra and dilutions).

ARCADIS G&M, Inc.
4915 Prospectus Dr.
Suite F
Durham
North Carolina, 27713
Tel 919 544 4535
Fax 919 544 5690

MEMO

Subject:
Validation of Water Samples Collected at
Hanscom AFB 11/19-20/2001

Date:
8/8/02

From:
Dennis Tabor

Drafted by:

Department:

ARCADIS Project No.:
RN009900.0017.00001

To:
Chris Lutes

Copies:

Eleven samples were collected on November 19th and 20th, 2001 at Hanscom AFB, Massachusetts. These samples and a trip blank were submitted on November 20th, 2001 to Severn Trent Laboratories (STL) Savannah Facility in Savannah Georgia for analysis. This validation covers the samples submitted for Volatile organics by United States Environmental Protection Agency (USEPA) Method SW-846 8260B. Other aliquots were analyzed for other parameters that were not discussed in this memo.

Validation of this data was performed following the quality assurance/quality control (QA/QC) criteria set forth in the "USEPA Contract Laboratory Program (CLP) National Functional Guidelines for Organic Data Review", revised in June 2001. Method 8260B has slightly different criteria for some parameters than the CLP. Therefore, when the criteria were different and the 8260B criteria were more stringent the 8260B criteria were used.

This project is focused on the chlorinated ethenes. Trichloroethene was the primary compound of interest. Acetone and other ketones were of secondary interest.

It is the reviewer's opinion that the quality of the data was barely acceptable with the qualifiers discussed below.

Sample Delivery Group: HAFB02

Volatile Organic Data

I Preservation

There is no indication in the report that the samples were checked for Temperature, headspace or pH upon arrival at the lab. The run log has a note “see log in” under the pH column. No login sheet with pH information was found. Preservation was indicated on the Chain-of-Custody (COC) for all the samples. The samples were analyzed within the Acid-preserved hold time criteria of 14 days.

II Gas Chromatography/ Mass Spectrometer (GC/MS) Instrument Performance Check

Bromofluorobenzene checks were done successfully on the Initial Calibrations and Analysis days. The lab used CLP BFB abundance criteria not 8260B. The tune checks passed the CLP Criteria but not the 8260B. 8260B criteria are more stringent that CLP. This difference is minor and would not cause question on the data. The lab should be more careful to use the criteria from a method if it is quoted as the method being done.

III Initial Calibration

All of the Chloroethenes, Ketones, and the Deuterated Monitoring Compounds (DMCs) had Response Factors above 0.05in the Initial Calibration (IC). The range was from 5 to 1000 ng introduced to the column. (ketones 10 to 2000) Relative Standard Deviations (RSDs) were below 15% for the Chloroethenes and the DMCs. Some ketones were too high in variability. The Ketone data should not be used for precise quantitation.

IV Continuing Calibration

The Continuing Calibration (CC) was run in the 12-hour analysis window before any of the samples were analyzed. The CC had RFs above 0.05 for the Chloroethenes, Ketones, and the DMCs. The Relative Percent Deviations (RPDs) from the IC were below 15% for one of the DMC and half of the Chloroethenes. Trichloroethene was at 26% deviation. Looking at the trends it appears that the standard may have been poorly made up. Most of the compounds are in the 15 to 25% deviation range. The CCC compounds from 8260B passed the 20% requirement. But since the compound of main interest was trichloroethene the calibration should have been rerun.

V Blanks

All blanks reported non-detect for all compounds of interest.

VI Deuterated Monitoring Compounds (DMCs)

All criteria were met for all samples. The specified criteria on the reports are neither CLP nor 8260B. The recoveries look fine but if in-house recovery limits are being used it should be noted in the case narrative. The stated limits are much wider than 8260B and are greater than what was being used in the previous laboratory on this project.

VII Matrix Spike/ Matrix Spike Duplicates (MS/MSDs)

MS/MSD appeared in the run log in the batch and was project specific. There were apparent compounds that had been spiked and they were of similar concentration, but there was no information on spike levels or recovery so evaluation could not be done. The matrix spike and Dup have several compounds listed that appear to be off of retention time. They are not the usual spiked compounds so they may have just not been deleted during QC. These off-time compounds will not effect the usefulness of the data.

VIII Regional QA/QC

Not Applicable

IX Internal Standards

All criteria were met.

X Target Compound Identification

No mis-identifications were noticed.

XI Compound Quantitation and Reported Contract Required Quantitation Limits (CRQLs)

Reporting limits were fine for this project. The lab is to be commended for reporting all detected values in both the initial and diluted runs.

The lab appears to have had prior knowledge of which samples would require dilution or screened the samples.

XII Tentatively Identified Compounds (TICs)

Not Applicable

XIII System Performance

No problems noted.

XIV Overall Assessment of Data

The data appears to be good, but with some problems.

ARCADIS G&M, Inc.
4915 Prospectus Dr.
Suite F
Durham
North Carolina, 27713
Tel 919 544 4535
Fax 919 544 5690

MEMO

Subject:
Validation of Water Samples Collected at Hanscom AFB 3/27-28/2002

Date:
7/26/02

From:
Dennis Tabor

Drafted by:

Department:

ARCADIS Project No.:
RN009900.0017.00001

To:
Chris Lutes

Copies:

Eleven samples were collected on March 27th and 28th 2002 at Hanscom AFB, Massachusetts. These samples were submitted on March 29th 2002 to Severn Trent Laboratories (STL) Savannah Facility in Savannah Georgia for analysis. This validation covers the samples submitted for Volatile organics by United States Environmental Protection Agency (USEPA) Method SW-846 8260B. Other aliquots were analyzed for other parameters that were not discussed in this memo.

Validation of this data was performed following the quality assurance/quality control (QA/QC) criteria set forth in the "USEPA Contract Laboratory Program (CLP) National Functional Guidelines for Organic Data Review", revised in June 2001. Method 8260B has slightly different criteria for some parameters than the CLP. Therefore, when the criteria were different and the 8260B criteria were more stringent the 8260B criteria were used.

This project is focused on the chlorinated ethenes. Trichloroethene was the primary compound of interest. Acetone and other ketones were of secondary interest.

It is the reviewer's opinion that the quality of the data was acceptable with the qualifiers discussed below, for all samples.

Sample Delivery Group: HAFB06

Volatile Organic Data

I Preservation

There is no indication in the report that the samples were checked for Temperature or pH upon arrival at the lab. Preservation was indicated on the Chain-of-Custody (COC) for all the samples. The samples were analyzed within the Acid-preserved hold time criteria of 14 days. Two samples did not have analysis requested on the original COC but it is assumed that the lab discussed this with the project officer (but not noted) because the copy of the COC has indications that are not on the original COC. Both were in the report.

II Gas Chromatography/ Mass Spectrometer (GC/MS) Instrument Performance Check

Bromofluorobenzene checks were done successfully on the Initial Calibrations and Analysis days. The lab used CLP BFB abundance criteria not 8260B. The tune checks passed the CLP Criteria but not the 8260B. 8260B criteria are more stringent that CLP. This difference is minor and would not cause question on the data. The lab should be more careful to use the criteria from a method if it is quoted as the method being done.

III Initial Calibration

All of the Chloroethenes, Ketones, and the Deuterated Monitoring Compounds (DMCs) had Response Factors above 0.05in the Initial Calibration (IC). The range was from 5 to 1000 ng introduced to the column. (ketones 10 to 2000) Relative Standard Deviations (RSDs) were below 15% for the Chloroethenes and the DMCs. Most ketones were too high in variability. The Ketone data should not be used for precise quantitation.

IV Continuing Calibration

The Continuing Calibration (CC) was run in the 12-hour analysis window before any of the samples were analyzed. The CC had RFs above 0.05 for the Chloroethenes, Ketones, and the DMCs. The Relative Percent Deviations (RPDs) from the IC were below 15% for the DMC and half of the Chloroethenes. Half of the Chloroethenes were between 15 and 20%. The ketones were also high on variability in the CC with only half of the target ketones better than 15%.

V Blanks

All blanks reported non-detect for all compounds of interest. One lab blank had 123-trichloropropane at one half the lowest calibration level but that compound is not one of the compounds of interest.

VI Deuterated Monitoring Compounds (DMCs)

All criteria were met for all samples. The specified criteria on the reports are neither CLP nor 8260B. The recoveries look fine but if in-house recovery limits are being used it should be noted in the case narrative. The stated limits are much wider than 8260B and are greater than what was being used in the previous laboratory on this project. The recoveries would have failed about half the time if the method specified limits were used.

VII Matrix Spike/ Matrix Spike Duplicates (MS/MSDs)

MS/MSD appeared in the run log in the batch but was project specific. It looked fine.
The laboratory control spikes were well reported and were acceptable.

VIII Regional QA/QC

Not Applicable

IX Internal Standards

All criteria were met.

X Target Compound Identification

No mis-identifications were noticed.

XI Compound Quantitation and Reported Contract Required Quantitation Limits (CRQLs)

Reporting limits were fine for this project. The lab is to be commended for reporting all detected values in both the initial and diluted runs.

The lab appears to have had prior knowledge of which samples would require dilution or screened the samples.

XII Tentatively Identified Compounds (TICs)

Not Applicable

XIII System Performance

No problems noted.

XIV Overall Assessment of Data

The data appears to be very good, with only minor problems.

ARCADIS G&M, Inc.
4915 Prospectus Dr.
Suite F
Durham
North Carolina, 27713
Tel 919 544 4535
Fax 919 544 5690

MEMO

Subject:
Validation of Water Samples Collected at Hanscom AFB 10/15/2002

Date:
11/12/02

From:
Dennis Tabor

Drafted by:

Department:

ARCADIS Project No.:
RN009900.0017.00001

To:
Chris Lutes

Copies:

Five samples were collected on October 15th, 2002 and Two samples were collected on October 16th, 2002 at Hanscom AFB, Massachusetts. These samples and a trip blank were received on October 16th and 17th, 2002 to Severn Trent Laboratories (STL) Savannah Facility in Savannah Georgia for analysis. This validation covers the samples submitted for Volatile organics by United States Environmental Protection Agency (USEPA) Method SW-846 8260B. Other aliquots were analyzed for other parameters that were not discussed in this memo.

Validation of this data was performed following the quality assurance/quality control (QA/QC) criteria set forth in the “USEPA Contract Laboratory Program (CLP) National Functional Guidelines for Organic Data Review”, revised in June 2001. Method 8260B has slightly different criteria for some parameters than the CLP. Therefore, when the criteria were different and the 8260B criteria were more stringent the 8260B criteria were used.

This project is focused on the chlorinated ethenes. Trichloroethene was the primary compound of interest. Acetone and other ketones were of secondary interest.

It is the reviewer’s opinion that the quality of the data was very good. With the exception that ketones in one sample were misidentified as present. The compounds do not appear to be the targets in question but are there and large.   When requested the laboratory evaluated the data again and agreed that the compounds were not the targets and removed them from the report.

Sample Delivery Group: HAFB10

Volatile Organic Data

I Preservation

There is no indication in the report that the samples were checked for Temperature, headspace or pH upon arrival at the lab. No login sheet with pH information was found. Preservation was indicated on the Chain-of-Custody (COC) for all the samples. All but one of the samples were analyzed within the non-acid-preserved hold time criteria of 7 days. The last sample was analyzed within the Acid-preserved hold time of 14 days.

II Gas Chromatography/ Mass Spectrometer (GC/MS) Instrument Performance Check

Bromofluorobenzene checks were done successfully on the Initial Calibrations and Analysis days. The lab used CLP BFB abundance criteria not 8260B. The tune checks passed the CLP Criteria and the 8260B. 8260B criteria are more stringent that CLP. This difference is minor and would not cause question on the data. The lab should be more careful to use the criteria from a method if it is quoted as the method being done or specify what criteria are being used.

III Initial Calibration

All of the Chloroethenes, Ketones, and the Deuterated Monitoring Compounds (DMCs) had Response Factors above 0.05in the Initial Calibration (IC). The range was from 5 to 1000 ng introduced to the column. (ketones 10 to 2000) Relative Standard Deviations (RSDs) were below 15% for the Chloroethenes and the DMCs.

IV Continuing Calibration

The Continuing Calibration (CC) was run in the 12-hour analysis window before any of the samples were analyzed. The CC had RFs above 0.05 for the Chloroethenes, Ketones, and the DMCs. The Relative Percent Deviations (RPDs) from the IC were below 15.

V Blanks

All blanks reported non-detect for all compounds of interest.

VI Deuterated Monitoring Compounds (DMCs)

All criteria were met for all samples. The specified criteria on the reports are neither CLP nor 8260B but would has easily passed them. The recoveries look fine but if in-house recovery limits are being used it should be noted in the case narrative. The stated limits are much wider than 8260B.

VII Matrix Spike/ Matrix Spike Duplicates (MS/MSDs)

The MS/MSD was not project specific. So evaluation could not be done.

VIII Regional QA/QC

Not Applicable

IX Internal Standards

All criteria were met.

X Target Compound Identification

2-Butanone and 4-methyl-2-Pentanone were mis-identified in Sample HAN-GW-IRZ-INJ From 10/15/02. When requested the laboratory evaluated the data again and agreed that the compounds were not the targets and removed them from the report. No other mis-identifications were noticed.

XI Compound Quantitation and Reported Contract Required Quantitation Limits (CRQLs)

Reporting limits were fine for this project.

The lab appears to have had prior knowledge of which samples would require dilution or screened the samples.

XII Tentatively Identified Compounds (TICs)

Not Applicable

XIII System Performance

No problems noted.

XIV Overall Assessment of Data

The data appears to be good. With the exception that ketones in one sample were misidentified as present. The compounds do not appear to be the targets in question but are there and large.

Appendix A-6c

QC Notes

Appendix A-6c: Summary of QA/QC Observations – ESTCP/AFCEE IRZ Project

Hanscom AFB

Well Installation May 2000
Field Duplicates in soil sampling: The field crew initially failed to collect the required field duplicate. The laboratory was given instructions to analyze two of the multiple containers collected for one sample to constitute the field duplicate.

First Full – Background Sampling Round – June 2000
Hydrogen: The lab (Vaportech) did not receive any vial labeled HAN-SG-IRZ-1-1 as indicated on the custody sheet. They received 2 vials labeled HAN-SG-IRZ-INJ-1. There were no further clues to identity on the vials. Both of the vials had the same value when analyzed >50nM/l, therefore the error was inconsequential.

Field blank (HAN-GW-FB-1) 6/12/00 15:15 gave a DOC at 9.5 mg/l and COD at 185 mg/l suggesting the presence of some organics. This field blank was prepared using distilled water purchased at a supermarket, which may be subject to some organic leaching from the container.

Ferrous Iron: Field kits were used for the 0-1 and 1-10 mg/l ranges, however many wells were reported as >10 mg/l. Note that a laboratory measurement is available however so this is not a major impediment to data interpretation.

DO: Problems were experienced with the original YSI probe for DO leading to a switch to the Horiba and repeat of some measurements. We also asked Vaportech to repeat this measurement offsite as a backup.

ORP, Injection Well: Two instruments were used. The Horiba data was 200 mv and the YSI –33.4. The Horiba data is reported for consistency with other measurements but the YSI value is more consistent with other wells measured at that time. For other wells the Horiba and YSI values agree fairly well for this parameter.

December 2000
A discussion was held with the offsite analytical laboratory when it was noted that the cis and trans DCE did not add up to the total DCE. They explained that unique calibration curves were used for these three analyses so they might not add up exactly. In short the response factor for "Total" is a function of the "cis" and "trans" response factors. Since our reporting is almost always in terms of the individual isomers this was judged to be unimportant

April 2001 abbreviated monitoring
A discussion was held with the offsite analytical laboratory in May when a difference of more then an order of magnitude was noted between two analyses of the same CAH analyte at differing dilutions in an injection well sample. The laboratory reviewed the situation and reported that one of the analyses was being effected by a positive interference which was then taken into account in data analysis.

May 2001 Full Monitoring Round
A non-detect for bromide at an elevated detection limit in an injection well sample was discussed with the offsite analytical laboratory. It was determined that a high chloride value made dilution necessary.

July 11, 2001 Process Monitoring
An unusual conductivity reading was investigated and determined to be due to a failure by the field staff to note an automatic change in units from ms/cm to s/m on the instrument in bright sunlight, the data was revised.

October 12, 2001 Process Monitoring
Tom Best of Hanscom reported that some samples from another area of the facility analyzed in the same batch with our samples showed anomalous results based on his detailed site knowledge. IT Corporation resampled some of the wells on October 19th. Since these results were more consistent with expectations they were used.

TOC results from the offsite lab were only 2.9 mg/l although the well was described in the field as "light brown" and with an odor of molasses. The laboratory pulled out the samples and determined that the TOC fraction was clear and colorless. The offsite lab was instructed to measure the TOC on the fraction that was originally collected for Bromide analysis. Although this sample was colored a TOC of only 3.4 mg/l was seen. The lab then attempted to determine if the TOC preservation procedure was the cause of the problem. To do this the acidified the Br sample but it did not change color. It was inferred that biodegradation may be continuing in the sampled, preserved TOC samples.

December 2001
The offsite lab was requested to confirm results after recent DOC values were observed to be higher then TOC. The results were confirmed by reanalysis.

Process Monitoring January 22, 2002:
Upon review by the project engineer and manager pH data were higher by 1-2 units then the expected value and one reading was far off scale. Since records indicated that the injection well was measured first and had a very high TOC loading it was suspected that it fouled the electrode. The results were discarded and the field crew was advised on methods to avoid this problem in the future.

Process Monitoring June 6, 2002:
An abnormally high DO value measured in this round in the injection well was investigated and attributed to fouling by the very high concentration of organics present.

Final Full Sampling Round October 14-16, 2002
The field staff initially failed to report a complete set of visual and olfactory data as had been requested. However they were able to provide it in an email several days later.

Results for DO and pH for this monitoring round collected in the field appeared suspect upon review by the project engineer and manager because they fell out of expected ranges. DO data also did not agree with the data from the off-site laboratory within reasonable tolerances for some samples that were measured with one particular meter. It was then determined that the field staff had failed to adequately follow calibration procedures on this occasion, a failure they attributed to a vendor not providing expected materials. The field staff were reminded of proper procedures and ARCADIS repeated these measurements at its expense on October 29, 2002. During that event calibrations were properly performed and values recorded within expected ranges for nearly all parameters. However the injection well water was visibly effervescing and gave a reading that was off-scale even after meter recalibration.

Appendix A-7

Additional Discussion of Hydrogeologic Evaluations

Appendix A-7: Additional Discussion of Hydrogeological Evaluations

Changes in Groundwater Flow Direction Due to Changes in Pumping Rates

The ERD at Hanscom exhibited changes in groundwater flow that were not expected and led to complex patterns in substrate delivery and CAH concentration as discussed above. The most probable explanation for these changes is a combination of multiple sources and changing pumping patterns imprinted on top of a complex geology with relatively thin aquifer zones.

The geology of the area is a glacial valley fill on top of granitic bedrock. The general sediment sequence at the area of the IRZ/ERD demonstration from top down is a layer of fine sand on top a discontinuous layer of clay on top of a sandy till (see Figures 3-3 and 3-4). This sequence is on top of fractured granite, with some fractures filled with silt. The most hydraulically conductive layer is the lower sandy till with a hydraulic conductivity of 1 to 25 feet per day. The active IRZ/ERD is within this layer of sandy till. The fine sand above and the fractured bedrock are about a tenth as conductive as the till. The discontinuous clay is considerably less conductive than the till. All three of the sedimentary units are not present over the entire site, and all have areas of zero thickness (Haley and Aldrich, September, 1998). The granitic bedrock is present over the entire area of interest. The general flow direction in the three conductive units, the upper sand, the basal sandy till, and the fractured bedrock, is basically east (CH2M Hill, 1997).

Even this generalization about the “sandwich” of three sediment types is oversimplified. While at the area of the IRZ/ERD the general sequence is found, Haley and Aldrich, 1998, report that at Hartwell’s Hill, the upper two units are absent and only the lower sandy till is present. Given the changes in thickness and in continuity of all three layers, CH2M Hill (1997) chose to model the area in horizontal layers with considerably different hydraulic conductivities in cells in the same layer. While this approach is reasonable, it does not allow the interpretation of the results of the Hill modeling to be taken to site-specific instances within the framework of the three recognized layers in the unconsolidated and the one bedrock layer. In simple terms, the output of the Hill model is not easily understood as to the hydrogeological unit that is presented. Nonetheless the Hill model is useful tool for a gross understanding.

The important features of the hydrogeology are:

- The most productive unit, the sandy till, is semi-confined over the entire area and in the area of active IRZ/ERD, and
- it is at most about 20 feet thick.

The confinement means that changes in withdrawals are expected to show effects much more quickly than in unconfined conditions. The quickness of reaction over larger areas is the result of the fact that in confined aquifers, unlike unconfined aquifers, the removal of large amounts of water is not needed to affect changes in head over relatively large areas because head is being transmitted, not water.

There are two recovery trenches, numbers one and two, and five recovery wells, numbers BIW1 through BIW-4 and BIW-6, in the area of the IRZ/ERD (see Figure 3-1 for the location of these features and Figure 4-28 for the pumping rates). Both recovery trenches are in the upper sand only. Recovery Trench 1 is just to the northwest of the IRZ/ERD area, and Recovery Trench 2 is to the southeast. But, as both penetrate only the upper sand and not the lower till, their only effect is to deny possible leakage through the confining clay in the case of Trench 1. Trench 2, which is basically downgradient, would have little or no effect on the demonstration. Little impact is discernable from the two to three-fold changes in recovery at the two trenches in 2000 and 2001.

Four of the five recovery wells are arranged in an arc to the north and east of the IRZ/ERD area (Figure 3-1). BIW-1 is just about 1300 feet due north of the IRZ/ERD area. BIW-2 is about 1250 feet northeast. BIW-4 is about 1300 feet east, and BIW-3 is about 1500 feet southeast. In all of these wells (BIW-1 through 4), the sand is well confined by lacustrine clay that is apparently reasonably widely distributed in the areas of the wells. All of these wells, except BIW-1 extract about two-thirds of their water from the lower sandy till and the rest from the bedrock. In BIW-1, this ratio is reversed (CH2M Hill, 1997). In BIW-1, the lower unconsolidated productive zone is 12 feet thick, and the screen is set with 8 feet open to that zone and 53 feet open to the bedrock. Additionally, the contact of till and granite is at the 100-foot elevation, 30 feet higher than at the IRZ/ERD area. In contrast, at BIW-2 through 4, the lower productive unconsolidated zone is much lower in elevation, ranging from 60 feet to below 40 feet, or 10 to 30 feet lower than in the IRZ/ERD area. Therefore, because of the distance from the IRZ/ERD and the elevation of the base of the unconsolidated deposits, the effect of pumping at BIW-1 will be less than at BIW-2 through 4 on groundwater flow in the IRZ/ERD area. BIW-6 is about 500 feet west-northwest of the demonstration zone. It was installed in 1997, after the data collected for the CH2M Hill modeling work, and withdraws at a relatively constant flow rate from the bedrock aquifer (Hanscom AFB, 2002; see also Figure 4-28).

Groundwater withdrawal from BIW-2 has been relatively constant at about 275,000 gallons per month respectively. Pumpage at BIW-1 has not been as constant, but generally is about 750,000 to 850,000 gallons per month. Pumping from BIW-4 was fairly constant at 500,000 gallons per month until the pump was changed and the flow increased to arround 1,100,000 gallons per month in November 2001. It stayed at this higher level through the end of the demonstration except for August and September 2002 when it was much lower. The withdrawal from BIW-3, however, due to a variety of operational reasons, has ranged from 0 gallons per month in September and October 2000, and again in May 2001, to over 2,000,000 gallons per month in December 2000 and most of 2001. It pumped over 2,000,000 gallons per month for all of the demonstration period in 2002 except for slight dips in July and August. It is thus likely that the production changes in BIW-3 and BIW-4 had the biggest effect on the direction of groundwater flow in the basal sandy till in which the demonstration occurred.

In 2000, withdrawal from BIW-3 from January to late August averaged approximately 850,000 to 900,000 gallons per month. In September and October 2000, no water was withdrawn. Around 600,000 gallons were withdrawn in November 2000 and more than 2,000,000 gallons in each of the next four months. If the potentiometric map from mid-June 2000 (Figure 4-9) is compared with those of December 2000 (Figure 4-10) and January 2001 (Figures 4-13 and 4-14), a marked shift in flow direction is seen from east to southeast and back to east. Since no potentiometric surface is available for September and October 2000, it is likely that even more marked changes occurred that were not observed.

In 2001, BIW-3 generally pumped between 1,700,000 and 2,500,000 gallons per month but was off in May, and the potentiometric surface observed in May (Figure 4-11) clearly changed from that seen in April (Figure 4-16). In April, the head contours were basically aligned north-south and the flow was east or east by northeast. In contrast in May, the flow was to the northeast, when the pump at BIW-3 was not operating. After returning the pump to operation, the flow eventually returned to a more easterly direction (Figures 4-17 through 4-19 and 4-12).

Finally, from the pumping perspective, the production from well BIW-4 was increased markedly starting in October 2001. The production at the well jumped from roughly 500,000 to 600,000 gallons per month to 1,120,000 and 1,240,000 gallons per month in November and December 2001, respectively. This increase also would swing the flow more directly easterly, as BIW-4 is directly east of the IRZ/ERD area.

In 2002, pumping rates were quite constant from January to June and flow appeared to be consistent in the easterly direction from (Figures 4-20 through 4-22). The rate in BIW-3 decreased somewhat in July and August due to maintenance problems. The rate in BIW-4 was sharply lower in August and September. As shown in Figure 4-23, this appears to have increased the relative influence of the upgradient well BIW-6, resulting in a flow divide between easterly and westerly flow being located somewhere under the runway outrun between B239 and IRZ-INJ for a time. Flows had returned to a normal easterly direction in September through October 2002 (Figures 4-24 through 4-27).

These changes in flow direction no doubt affected substrate delivery and thus treatment efficiency. The basic assumption made in setting up the injection and monitoring wells is that the direction of groundwater flow and hence contaminant and substrate transport is relatively stable in a southeasterly direction. As discussed, the maps of head in the basal sandy till show that the orientation of the head contours has not been stable. In fact, that orientation has responded to the changes in pumpage in the basal sandy till, especially changes in BIW-3 and to a lesser degree in BIW-4. As discussed previously while the reduction in the parent compound, TCE, has generally been favorable in the two monitoring wells that fell within the reactive zone, there have been excursions from that trend. Two of the most notable were in late 2000, when a precipitous drop was followed by a sharp rise (see Figure 4-37), and in fall and winter 2001. The late 2000 changes came immediately after shutting off BIW-3 followed by very high rate of withdrawal from BIW-3 (0 in September and October, 655,000 gallons in November, and 2,080,000 gallons in December). The second occurred primarily in fall and winter 2001 and coincided with the increase in pumpage in from BIW-4 (from less than 630,000 gallons each month before September 2001 to more than 1,100,000 gallons per month from October 2001 to July 2002).

In summary, the changes in pumpage from wells BIW-3 and BIW-4 have induced changes in the flow regime at the IRZ/ERD area in the basal unit that help explain the variations in substrate delivery and treatment efficiency.

Groundwater Velocity Estimation

Based on preexisting data we estimated the groundwater flow velocity at the site to be 0.8 ft/day (ARCADIS Geraghty & Miller 2000). Groundwater velocity observed in the demonstration area was calculated using three methods:

a) Based on average bromide concentrations observed at the first line of observation wells (IRZ-1 and RAP1-6T) and the mass bromide loading rate at the injection well, a volumetric flow rate through the lower aquifer was estimated and used to derive a flow velocity. In this calculation the average bromide concentrations at IRZ-1 and RAP1-6T since their first appearances (1.9 mg/l and 5.9 mg/l, respectively) were used to calculate an average bromide concentration (3.9 mg/l) at the "flow window" described by these two wells. The "flow window" of 30 feet wide by 20 feet deep (the thickness of the lower aquifer) has an estimated effective porosity of 15%, giving a flow area of 30 feet x 20 feet x 0.15 = 90 square feet. In the course of the demonstration, 4732 grams of bromide were injected with 20,075 gallons of liquid, for an average injection concentration of 62.3 mg/l bromide. The dilution ratio was calculated as 62.3mg/l ÷ 3.9 mg/l = 16. Therefore, 20,075 gallons x 16 = 320,685 gallons of liquid (groundwater plus injection fluid) passed through the flow window during the demonstration, over a period of 734 days. The daily flow rate through the window was 320,685 gallons ÷734 days = 436 gallons per day, or 58 cubic feet per day. This amount of flow through a 90 square foot flow area would occur at a velocity of 0.64 feet/day.

b) The bromide arrival time at the first line of observation wells was used to calculate flow velocity. The bromide data show initial increases in concentration at these wells within a month of the first injection, and consistently low concentrations until early 2001, when substantial increases occur. Thus, both dates were used to estimate a range of velocity values.

   The first bromide detections at IRZ-1 and RAP1-6T occurred within 27 days after the first injection (see November 7, 2000 data). This interpretation of arrival time is supported by the simultaneous increase in TOC at IRZ-1 and decreases in DO at IRZ-1, RAP1-6T and other monitoring wells. Alternately, the first arrival of higher bromide concentrations occurred between 112 and 166 days after the first injection. The midpoint of approximately 140 days was assumed to be the arrival time for this calculation. The distances of the downgradient wells from the injection well are approximately 45 feet (INJ-1) and 40 feet (RAP1-6T). Using the average travel distance of 42.5 feet, the maximum bromide velocity was at least 42.5 feet ÷27 days = 1.57 feet/day, and the minimum velocity was 42.5 feet ÷ 140 days = 0.30 feet/day.

c) Measured or estimated values of hydrogeologic characteristics were used to calculate flow velocity based on a variation of Darcy's Law. The average linear groundwater flow velocity in the direction parallel to flow is given by:

$$v_x = \frac{KI}{n_e}$$

where:

v_x = average linear groundwater flow velocity (ft/day);

K = hydraulic conductivity (ft/day) – for the lower aquifer, ranges from 3 to 35 ft/day, based on slug test results (CH2M Hill, 1997)

I = hydraulic gradient (unitless) – typically 0.006 over the course of the demonstration; and

n_e = effective porosity (unitless) – estimated to be 0.15.

Using an average hydraulic conductivity of 19 feet/day, the flow velocity was calculated by this method to be 0.76 feet/day.

Thus these three methods provided estimates of velocity that agree fairly closely:

a) 0.64 ft/day

b) 0.30 to 1.57 ft/day

c) 0.76 ft/day

Method b) is the most direct measure of velocity during the test. However, it may overestimate velocity during normal conditions because of the force of the initial injections. On the other hand it could underestimate velocity if the bromide tracer was not fully conservative (i.e., was adsorbed to soil particles or taken up in biomass or if the initial injection rate of molasses/ bromide was too low and thus became too diluted to provide a significant increase over the background concentration. Method a) probably overestimates velocity because it assumes all of the injected water travels through a 20x30 window. Method c) may also overestimate normal velocity because slug tests typically overestimate hydraulic conductivity. The values derived from the three methods are reasonably close, thus an average velocity during the demonstration period of approximately 0.80 ft/day is assumed.

Appendix A-8

Additional Discussion of Secondary Water Quality Issues

Appendix A-8: Additional Discussion of Secondary Water Quality Issues

Secondary Water Quality Issues

We recognize that while the substrate injected (molasses) and its breakdown products are generally nontoxic, it may elevate certain parameters in the water within the reactive zone. For example, by definition, any substrate used to enhance anaerobic bioremediation will elevate the biological oxygen demand (BOD), a traditional measure of water quality. Furthermore, since we are intentionally creating reducing conditions within the reactive zone, this will necessarily alter the geochemistry of the reactive zone. This will make some soil mineral metals more mobile (more dissolved) and others less mobile (more inclined to the solid phase). Further information about these matters can be found in Sections 1.2, 2.1, 3.1 and 7 of the protocol document (Suthersan, 2002).

In general, it is believed that enhanced anaerobic in-situ bioremediation processes will reduce the mobility of many metals (indeed it has been successfully used for the treatment of many) but it will solubilize some other naturally occurring metals in the reactive zone (for example iron, manganese, and arsenic). This creates a potential secondary water quality impact. Other parameters of interest with regard to secondary water quality impacts are COD, BOD, TDS, and sulfides. However even in solubilized form under anaerobic conditions metals such as arsenic are substantially retarded by adsorption to the aquifer matrix. Furthermore it is generally believed that they will be reprecipitated/immobilized down-gradient of the reactive zone when the conditions return to their preexisting state (which for the purposes of this discussion is assumed to be aerobic). Similarly reprecipitation/immobilization will occur within the IRZ area some time after system shutdown. Finally, we note that these reducing conditions are by no means unique to IRZ systems – they occur for example at sites of TPH releases and landfills as well.

Finally, the substrate itself has been mentioned as a potential source of metals that may cause secondary water quality impacts. Molasses in its pure form contains concentrations of several metals that may exceed water quality criteria. In a dilute mixture, as is typically used in IRZ applications, the concentrations have been below regulatory standards. However, this is a potential issue that should be considered in the design phase.

Therefore, we agreed with ESTCP on a multi-step process to evaluate these issues in the context of the Hanscom demonstration:

1. <u>Review existing base monitoring data:</u> This was found to be of very limited utility since the only metals data available according to the restoration manager, Tom Best, are copper, lead and hardness in the upper aquifer, which is above our target zone. Furthermore, all of the available data was collected before the beginning of system operation. Thus it can only be an imperfect indicator of background for site groundwater.

2. Review mineralogy: Results of this effort are discussed below. This provides guidance for parameter selection and data interpretation but cannot be definitive.
3. Review data gathered to date in ESTCP Demonstration on iron, manganese, COD and BOD: This is discussed below.
4. Expand the final monitoring round for this project to include 12 total and 12 dissolved priority pollutant metals (including mercury) plus TDS in all 10 wells normally in use for this project plus well B242 (roughly 500 days downgradient of the injection point. The results of this approach are discussed below.
5. Incorporate analysis of data gathered on a related project: We are currently conducting a large pilot scale study and a related simultaneous bench scale column study for Fort Devens Massachusetts, an Army site. Fort Devens and Hanscom are approximately 25 miles apart but their mineralogy may be somewhat different. A key issue for the Fort Devens project, and the primary focus of the bench scale column study, is the mobilization of arsenic during treatment of CAHs. The column study is primarily focused on observing the rate of arsenic reprecipitation/immobilization under various conditions. The results of this analysis are discussed below.
6. Expand the rebound monitoring to include 12 total and 12 dissolved priority pollutant metals (including mercury) plus TDS in two wells (IRZ-1 and RAP1-6T) in the heart of the treatment zone (4 total and 4 dissolved metals samples with QA/QC).
7. Review available data for metals in molasses: Available data for molasses and molasses-water mixtures such as those used at the site were reviewed in conjunction with the review of subsurface metals impacts. The results of this review are discussed below.

Secondary Water Quality – Implications of Mineralogy for Metals Available to be Released

Our system is operating in the lower sandy till aquifer, which is also known as the sublacustrine unit. The sublacustrine unit is primarily composed of granite, with lesser amounts of quartz diorite and gneiss (Haley and Aldrich, 1998). This unit has substantial background flows of moderately aerobic water. Based on this mineralogy we can conclude that in the bulk solid matrix:

- Fe, Mn are likely present in percent quantities
- Ba, Zn, Cr, V, Pb are likely present at 10-100 ppm (mg/kg)
- Cu, As, Co are likely present at 1-10 ppm (mg/kg)

This information was then used as guidance in developing strategies for further testing.

Secondary Water Quality – Iron and Manganese – Time Series during Demonstration

Total iron and manganese were measured at the off-site laboratory in the full monitoring rounds (background, midpoint and final). The data in Figures 4-66 and 4-67 clearly show that these metals were elevated vs. the background well (B239) within the reactive zone (IRZ-1, RAP1-6T and the injection well) but were not elevated downgradient (i.e., IRZ-5).

Secondary Water Quality: All Metals – Final Full Sampling Round

Total and dissolved metals data for groundwater were collected for the purpose of evaluating the possibility of secondary water quality impacts from ERD implementation. The metals data are summarized in Tables 4-12 and 4-13. Samples for this evaluation were collected on October 14-16, 2002, approximately two years after the first molasses injection. Wells are listed in the table approximately in order from upgradient to downgradient, starting with background well B239-MW. However, it is noted that the wells are screened at different levels within the aquifer system. The majority of the listed wells, including B239-MW, the six IRZ wells, RAP1-6T and B242-MW, are screened in the lower aquifer, in which injections occurred. Screened intervals for RAP1-6S and RAP1-6R are in the upper aquifer and in bedrock, respectively.

In the summary tables, metals concentrations are compared to Federal drinking water standards or goals. These standards are not necessarily ARARs at this facility, but are provided to put the results in perspective.

A comparison of the total and dissolved metals results indicates little difference between the two. Their similarity suggests that the metals contained in the samples were predominantly dissolved, with minor amounts contained in suspended solids. Because of the similarity between the two data sets, the following discussions refer to both collectively, with exceptions as noted. In some cases, dissolved metals levels exceeded total levels slightly. These discrepancies are attributed to normal sample and analytical variability. Since manganese was collected primarily as a process monitoring parameter, the discrepancy is not considered to be critical.

A comparison of results for the background well to the injection well shows that concentrations of several metals were higher in the injection well [arsenic (As), beryllium (Be), chromium (Cr), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), nickel (Ni), selenium (Se), zinc (Zn)], suggesting solubilization in the reactive zone. The magnitude of the increase must be presented with a note of caution, since many of the background concentrations were non-detects or otherwise qualified. With this in mind, metals levels at IRZ-INJ were as much as 90 times background levels.

However, concentrations of the majority of the (potentially) solubilized metals fell to background levels within a few months' travel time from the injection well (i.e., at IRZ-1 and RAP1-6T). At these two wells, still within the strongly reducing zone (or reactive zone), the only metals remaining at levels higher than background were As, Fe, Mn and possibly Cr. Among these, the magnitude of the difference was usually less than fivefold. Then, by the time the groundwater reached the wells directly downgradient from the reactive zone (IRZ-5 and B-242), metals levels were not elevated over the upgradient well (B239), indicating that they had successfully been reprecipitated or sorbed at the edges of the reactive zone.

A detailed discussion by metal is provided below:

- Arsenic levels were two to five times the background level at IRZ-1 and RAP1-6T, and at one further downgradient well (IRZ-3). (Interpretation of the dissolved arsenic data is inconclusive because of blank contamination). This distribution may indicate an elevation of arsenic mobility within the reactive zone, but the effect does not appear to be widespread or pronounced at greater distances (see also Figures 4-68 and 4-69). Importantly, the arsenic concentration downgradient of the reactive zone does not exceed the standard and in the two directly downgradient wells (IRZ-5 and B242) is not elevated over background. The range of arsenic detections may also reflect normal sampling and analytical variability. Additional background groundwater samples would be required to make this determination.
- Iron levels were three to five times higher at IRZ-1 and RAP1-6T than at the background well. Further downgradient, iron levels were comparable to background, suggesting that increased iron mobility was limited to the reactive zone.
- Manganese levels were slightly higher than background within the reactive zone, and below background at downgradient wells. As with iron, any increased manganese mobility appears to have been limited to the reactive zone.
- The average chromium concentration at RAP1-6T is slightly higher than the background concentration, but lower than at downgradient wells IRZ-4 and B242-GW (total chromium only). The differences likely reflect normal sampling variability since chromium is typically less mobile under reducing conditions.

At other levels of the aquifer above and below the injection zone, no background data are available for comparison. However, arsenic and iron levels at RAP1-6S were generally higher than in the lower aquifer, which may indicate some influence by the injections, or merely reflect differences in the background water quality between the aquifers.

In summary, the metals results indicate that secondary water quality impacts may occur within the reactive zone during implementation of ERD as a result of increased mobilization/ solubilization of some metals. However, the effect appears to be limited to the injection area and to the extent of the strongly reducing zone. The metals data supports the concept that the affected metals, including arsenic, iron and manganese, are reprecipitated/immobilized downgradient of the reactive zone when conditions return to preexisting (less reducing) state. Similarly, it is expected that reprecipitation/immobilization will occur within the IRZ area some time after system shutdown.

Secondary Water Quality – Arsenic – Field and Bench Scale Observations from another DoD IRZ Site

Similar issues have been discussed during the implementation of pilot tests performed for DoD at another Massachusetts site. At the Devens Reserve Forces Training Area, ARCADIS conducted bench-scale and field-scale ERD pilot tests that were designed in part to test for arsenic mobilization. The following discussion is summarized from the Devens ERD Pilot Test Evaluation Report (ARCADIS, November 2002).

There appear to be three primary triggers that can cause the release/solubilization of geogenic arsenic, including development of high pH (greater than 8.5), the presence of high concentrations of competing anions (such as phosphate, bicarbonate, or silicate), and development of reducing conditions at circumneutral pH.

Within the anaerobic and reducing IRZ created by ERD technology, there is evidence that some control on arsenic solubility can be realized through the formation of low-solubility arsenic sulfide compounds. However, it is expected that the primary control on arsenic solubility will be provided by adsorption to and co-precipitation with hydrous ferric (iron) oxides under ambient oxidizing conditions.

Under the Devens site's normal aerobic groundwater conditions, both dissolved-phase arsenic and iron concentrations were below laboratory detection limits. In the field pilot, arsenic was solubilized in the pilot study area at levels greater than both the current and proposed MCLs for arsenic. However, field tests supported the expectation that the presence of soluble arsenic will be limited to the boundaries of reducing zones created by the ERD technology. Once the original aerobic and oxidizing poise of those reducing zones is restored, it is expected that dissolved arsenic will decrease to non-detectable levels. ERD application was therefore considered appropriate for treatment of CAHs provided the temporary presence of arsenic was appropriately monitored and managed.

In the bench-scale treatability study (flow-through column study), the initial aerobic poise of each of three soil columns was overcome by passing reduced groundwater containing dissolved concentrations of arsenic, iron, and manganese through the columns. Measurements of the three metals/metalloids and DO and ORP were recorded at intervals as the water was applied to the columns. After reducing conditions had been achieved, the aerobic poise of two columns was restored using two different oxidation techniques (air injection and hydrogen peroxide injection). Based on the treatability study results, the following observations were made:

- even under reducing conditions, the aquifer materials provided a significant level of control on arsenic solubility.
- the injection of air or hydrogen peroxide in the field can create an aerobic environment (most suitable for controlling arsenic solubility).

Thus, both empirical data from the Devens site and published research indicate that arsenic solubility as it relates to the use of ERD can be controlled, mitigating concerns associated with use of the technology.

Secondary Water Quality – BOD, COD and Sulfide

Time-series data for BOD and COD during the demonstration are presented in Table 4-4. In general, the data confirm that as expected elevated BOD and COD occurred at the injection well after injections began (BOD and COD are measures of injected molasses and its metabolic products just as TOC is). However, levels of both parameters were reduced by several orders of magnitude at the first line of observation wells (IRZ-1 and RAP1-6T), and returned to background levels at the second line of wells.

As shown in Figure 4-40, hydrogen sulfide shows a similar pattern – it is substantially elevated as would be expected under anaerobic (sulfate reducing) conditions in the injection well and RAP1-6T. Although spotty detections occur in other wells it stays below 0.1 mg/l in the two wells monitored most directly downgradient of the reactive zone (IRZ-5 and IRZ-3). This suggests that sulfide production is confined to the reactive zone and decreases rapidly downgradient.

Secondary Water Quality – Metabolic Byproduct VOCs

VOCs other than the target species for treatment (chlorinated ethenes and ethanes and trace carbon tetrachloride) that were detected during three full monitoring events are summarized in Table 4-11 along with potentially applicable regulatory standards. Among these VOCs of secondary interest are petroleum constituents (EDB, MTBE, toluene, xylenes) that are probably attributable to the historical fire training activities at the site, since they do not show a strong association with the reactive zone. Another species detected was methylene chloride, which is a common laboratory contaminant and rarely exceeded its MCL in the samples collected for this project.

Chloroform and carbon tetrachloride were also detected. Chloroform is a known disinfection byproduct and carbon tetrachloride is commonly found in tap water. Thus, they were likely introduced with the tap water used for injections (California Department of Health Services, Howard 1990). They were only rarely detected and never above their MCLs.

Dichlorodifluoromethane and styrene were each detected once, but well below their regulatory standards and thus are not of concern. 1,2,3-trichloropropane was also detected once, substantially above its regulatory standard. However given the rarity of its appearance it is probably not of great concern.

However the ketones (acetone, 2-butanone, 2-hexanone, MIBK) that were detected are probably byproducts of molasses biodegradation. Of these:

- Acetone and 2-butanone were present within the reactive zone, consistent with the idea that both are metabolic by-products. Neither persisted further downgradient and even within the reactive zone the concentrations were below regulatory levels.
- 2-Hexanone and MIBK, also possible metabolic byproducts, were present only at IRZ-5 directly downgradient of the zone. However they were well below their regulatory standards.

Thus, in summary, the risks posed by these expected metabolic byproducts of the degradation of food grade carbon sources are very low in comparison to the risks posed by the chlorinated constituents that are targeted for remediation (note that these metabolic byproducts rarely exceeded their regulatory levels, and as shown in Section 4.3.3.3.6, the chlorinated compounds, especially vinyl chloride, were present at several hundred times their regulatory levels!

Secondary Water Quality – TDS

TDS data for October 2002 are presented in Table 4-10. The data show that two years into the demonstration, with injections ongoing, TDS is elevated in the injection area. The October 2002 TDS concentration at IRZ-INJ exceeds the Federal Secondary Drinking Water standard for TDS of 500 mg/l. At the first transect of observation wells downgradient from the injection area (IRZ-1 and RAP1-6T), TDS levels are lower by two orders of magnitude. TDS levels at the farthest downgradient IRZ wells and MW-B242 range from 150 to 220 mg/l and are comparable to the background level of 130 mg/l. Thus like many of the other secondary water quality parameters TDS is elevated in the reactive zone but dramatically decreased downgradient.

The ratio of TDS to specific conductance, which in natural waters is expected to fall within the range of 0.55 to 0.86 (Friedman and Erdman, 1982), is elevated at IRZ-INJ and RAP1-6S. At the injection well, and possibly at RAP1-6S, the ratio is likely disrupted by the presence of the substrate. Since both TDS and specific conductance were collected primarily as process monitoring parameters, the discrepancy is not considered to be critical.

Secondary Water Quality – Metals in Molasses

Molasses in its pure form contains concentrations of several metals that may exceed water quality criteria. Published analyses of blackstrap molasses (US Sugar, 2001) and analyses of metals and chloride in molasses/water mixtures by ARCADIS are presented in Tables 4-14 and 4-15. The ARCADIS metals sample was from a commercial remediation site in Ohio where a different molasses source was used than at Hanscom, but the results should be similar for Hanscom. Also note that the water-to-molasses mixture used at the Ohio site was slightly more dilute than the Hanscom mixture. None of the metals detected exceeded available Federal MCLs, and would not if adjusted to match the more concentrated Hanscom mixture. In addition, the site metals data discussed above encompasses any solute quality issues. On the basis of this evidence, we would not typically expect to see water quality impacts from the molasses injectate. However, this is a potential issue that should be considered in the design phase. The paucity of available data suggests that further work should be done in this area.

Appendix A-9

Data Archiving and Demonstration Plans

Appendix A-9. Data Archiving and Demonstration Plans:

1.0 Data Formats

There are four broad classes of data that were collected in this project.

1. The field measurements of groundwater parameters (generally for biogeochemical conditions) and other field observations
2. Laboratory measurements of soil and groundwater parameters, both contaminants and indicators of biogeochemical conditions
3. Engineering data on the design and operation of treatment systems
4. Economic data on the treatment systems.

1.1 Class I Data. Class I data was recorded on standardized field forms, including groundwater sampling form, photograph log, daily log, well construction log, sample/core log, water sampling log, reagent injection log, chain of custody record, Hach analytical log, and soil core/sampling log as found in Appendix D of the demonstration plan.

Chain-of-custody procedures were followed as described in Sections 5.4.3.3 and 6.1 of the demonstration plan. A field log may also be used to supplement the forms with notes and drawings describing the location, field conditions, and method of sample collection and identification.

1.2 Class II Data. Class II data will generally be received in the form of formal reports from the analytical laboratories. Note however, ARCADIS also received almost all of the analytical data on concentrations in the form of electronic deliverables.

1.3 Class III Data. Class III data is of two types. Engineering designs were documented in AutoCAD files and printouts. Field operating data such as reagent doses, flow rates, and concentrations will be documented on standard forms in a manner similar to Class I data.

1.4 Class IV Data. Procedures for collection of class IV data are discussed in Section 7 of the demonstration plan.

2.0 Data Storage and Archiving Procedures

2.1 Class I Data Storage. Class I data form originals will be retained in the office local to the site (the Andover office near Boston, Massachusetts). The field note originals will be maintained at the location of our Andover, Massachusetts, office in the building file storage locker. Copies of these documents are maintained in the file storage warehouse associated with the Durham, North Carolina, office.

2.2 Class II Data Storage. Class II data, as discussed above, were received and stored in both paper and electronic formats, initially at a central project archive to be maintained in the Durham, North Carolina, office of ARCADIS. It is also anticipated that the analytical laboratories involved will maintain their own copies of this data set for a period of years. However, this cannot be relied upon since firms in the analytical laboratory business have a history of rapid change.

2.3 Class III Data Storage. Class III engineering design data will be archived to the central project file following preparation. Copies will also be maintained in any office preparing engineering designs. Field operating data will be handled in the same manner as class I data.

2.4 Class IV Data Storage. Class IV data will be collected as discussed in Section 7 of the demonstration plan and archived to the central project file in the Durham, North Carolina, office of ARCADIS.

2.5 Archiving Procedures. The central hardcopy project archives at the Durham, North Carolina, office of ARCADIS will be maintained largely on site until the final reports are finalized for this project. This archive will include all data, documentation, records, protocols, reports, and correspondence. The archive will be transferred off-site at the completion of the project and stored for at least five years in a commercial file storage warehouse operated by Iron Mountain, Inc., 130 Nova Drive, Morrisville, North Carolina. The masonry and steel construction of this facility protects from most natural and human threat. Iron Mountain is the sole tenant of the facility, thus eliminating any conflicts associated with a multi-tenant facility. The facility can only be accessed by card key entry. Only those on the authorized list have access to the facility. The facility is monitored 24 hours a day, 365 days a year, by Sonitrol Security Systems. They employ the following type of security measures: motion, sound, smoke and heat detectors, as well as laser-trigger alarms. The facility is protected against fire by an Early Suppression Fast Response (ESFR) 6 ln. CSC Central sprinkler system. Their current operating system for records management is Total Recall by DHS Associates, Inc., of Orange Park, Florida. A back up tape for the Iron Mountain Facilities records is created daily and sent off site to a secure vault location to ensure that the data is protected and can be restored in the event of an emergency. The property the facility is on has been determined by FEMA, as of March 3, 1992, to be located in the 500-year flood plain, Zone X on map number 37183CO284E, community number 370242 and 550 feet from the 100-year flood plain.

The central electronic project archive will also be maintained in the Durham, North Carolina, office of ARCADIS on the central office server. The directory that will be used is accessible only to the project manager, system administrator, and a small group of his direct reports. This server is backed up to tape daily by the system administrator; these tapes are maintained for at least three weeks. The server is backed up to tape monthly and these tapes are permanently retained. Tape storage takes place in an on site fire proof cabinet. At the completion of this project ARCADIS anticipates placing the primary data tables on CD for ease of storage and access.

2.6 Data Availability Following Key Personnel Changes. In order to ensure data availability following key personnel changes, the project manager will be notified of any change in the employment status of that employee either by the employee or their direct supervisor (such as an office manager). The project manager will immediately take action as appropriate in conjunction with operations management to ensure the integrity and readability of all data. Should the transition affect the project manager himself for some unanticipated reason, the principal investigator and quality assurance officer would work together to ensure the integrity and readability of all data.

3.0 Demonstration Plan Availability

These are available as needed from Chris Lutes, the ARCADIS Project Manager, whose contact information is in Appendix A.

Appendix A-10

Microbial Characterization Report

2340 Stock Creek Blvd.
Rockford TN 37853-3044
Phone (865) 573-8188
Fax: (865) 573-8133
Email: microbe@microbe.com

Microbial Analysis Report

Client: Glen Gordon
Arcadis
175 Cabot Street
Suite 400
Lowell, MA 01854

Phone: 978-937-9999

Fax: 978-937-7555

MI Identifier: 6agm   Date Rec.: 10/15/02   Report Date: 12/9/02

Analysis Requested: PLFA, VFA, DGGE/DHE

Project:

Comments:

All samples within this data package were analyzed under U.S. EPA Good Laboratory Practice Standards: Toxic Substances Control Act (40 CFR part 790). All samples were processed according to standard operating procedures. Test results submitted in this data package meet the quality assurance requirements established by Microbial Insights, Inc.

Reported by: ______________________

Reviewed by: ______________________

2340 Stock Creek Blvd.
Rockford TN 37853-3044
Phone (865) 573-8188
Fax: (865) 573-8133
Email: microbe@microbe.com

Microbial Analysis Report

Executive Summary

Three samples were collected on 10/14/02 to evaluate changes in the microbial communities after a molasses injection. Samples were collected from an upgradient control location (HAN-GW-B239) and downgradient (HAN-GW-1R21), and crossgradient (HAN-GW-RAP1-6T) of the injection area. The following analyses were used for this characterization:

- Phospholipid Fatty acid analysis
- Volatile Fatty Acids
- Denaturing Gradient Gel Electrophoresis
- Targeted Gene Detection for *Dehalococcoides ethenogenes*.(DHE)

Results from this study revealed the following key observations:

- Although minimal, biomass estimates were higher in the samples collected downgradient and crossgradient of the molasses injection.

- Compared to the upgradient sample, conditions in the downgradient (HAN-GW-RAP1-6T) and crossgradient (HAN-GW-1RZ1) samples appeared to be more anaerobic with increased biomarkers associated with the firmicutes (clostridium-like bacteria), and detectable VFA. Additionally, DGGE results identified three anaerobic bacteria within HAN-GW-1RZ1.

- A targeted gene detection for DHE confirmed the presence of this bacterium in HAN-GW-RAP1-6T and HAN-GW-B239.

Overview of Approach:

Phospholipid Fatty Acid Analysis

Determination of the phospholipid fatty acids (PLFA) in environmental samples is an effective tool for monitoring microbial responses to their environment. They are essential components of the membranes of all cells (except for the Archea, a minor component of most environments), so their sum includes all important actors of most microbial communities. There are three different types of information in PLFA profiles – biomass, community structure, and physiological status.

Biomass: PLFA analysis is the most reliable and accurate method available for the determination of viable microbial biomass. Since phospholipids breakdown rapidly upon cell death (21, 23) the PLFA biomass does not contain 'fossil' lipids of dead cells. The sum of the PLFA, expressed as picomoles (1 picomole = 1×10^{-12} mole) is proportional to the number of cells. The proportion used in this report, 20,000 cells/pmole, is taken from cells grown in laboratory media, and varies somewhat with type of organism and environmental conditions. Starving bacterial cells have the lowest cells/pmol, and healthy eukaryotic cells have the highest.

Community Structure:. The PLFA in an environmental sample is the sum of the microbial community's PLFA, and reflects the proportions of different organisms in the sample. PLFA profiles are routinely used to classify bacteria and fungi (19), and are one of the characteristics used to describe new bacterial species (25). Broad phylogenic groups of microbes have different fatty acid profiles making it possible to distinguish between them (4, 5, 22, 24). Table 1 describes the six major structural groups employed in this report.

Table 1. Description of PLFA structural groups.

PLFA Structural Group	General classification
Monoenoic (Monos)	Abundant in Proteobacteria (Gram negative bacteria), typically fast growing, utilize many carbon sources, and adapt quickly to a variety of environments.
Terminally Branched Saturated (TerBrSats)	Characteristic of Firmicutes (Low G+C Gram-positive bacteria), and also found in Bacteriodes, and some Gram-negative bacteria.
Branched Monoenoic (BrMonos)	Found in the cell membranes of micro-aerophiles and anaerobes, such as sulfate- or iron-reducing bacteria
Mid-Chain Branched Saturated (MidBrSats)	Common in Actinobacteria (High G+C Gram-positive bacteria), and some sulfate-reducing bacteria.
Normal Saturated (Nsats)	Found in all organisms.
Polyenoic	Found in Eukaryotes such as fungi, protozoa, algae, higher plants, and animals.

Physiological status: The membrane of a microbe must adapt to the changing conditions of it's environment, and these changes are reflected in the PLFA. Toxic compounds or environmental conditions which disrupt the membrane cause some bacteria to make trans fatty acids from the usual cis fatty acids (7). Many Proteobacteria and others respond to starvation or highly toxic conditions by making cyclopropyl (7) or mid-chain branched fatty acids (20). The physiological status biomarkers for Toxic Stress and Starvation/Toxic conditions are formed by dividing the amount of the stress-induced fatty acid by the amount of it's biosynthetic precursor.

PLFA were analyzed by extraction of the total lipid (21) and then separation of the polar lipids by column chromatography (6). The polar lipid fatty acids were derivatized to the fatty acid methyl esters, which were quantified using gas chromatography (15). Fatty acid structures were verified by chromatography/mass spectrometry and equivalent chain length analysis.

Volatile Fatty Acids

The volatile fatty acids (VFA) pyruvate, lactate, formate, acetate, propionate, and butyrate are used as biomarkers of anaerobic metabolism. Anaerobic bacteria produce these compounds by fermentation, while under aerobic conditions, these compounds are rapidly oxidized for carbon and energy by aerobic bacteria. The VFA are analyzed by ion chromatography.

Denaturing gradient gel electrophoresis (DGGE)

Denaturing gradient gel electrophoresis (DGGE) is a powerful tool for detection and identification of organisms from environmental samples (1, 18, 12). In this method, sample microbial DNA is first isolated and purified. The DNA sequence for the Bacterial 16S ribosomal RNA (rDNA) is then amplified (many copies are made) using the polymerase chain reaction. The 16S rDNA gene is used for bacterial identification since it is common to all bacteria, and there are large databases of sequences available for comparison. The amplified sequences are separated into bands using a denaturing gradient gel. Numerically dominant members of the microbial community (>1 to 2% of the community) can be detected, so the bacterial identifications reported are examples of abundant members of the microbial community. For each sequenced DNA band, the closest described relative of each is reported. Phylogenetic affiliations are determined by comparing the rDNA sequences from samples to known bacterial sequences in the National Center for Biotechnology Information database (GenBank) (13). Recent progress in classifying Bacteria has caused many of the names used for bacteria and groups of bacteria to be changed. This can be a source of confusion since most scientists and engineers were trained when the earlier nomenclature was used. Table 2 shows the current names used in this report, and the corresponding obsolete terminology.

Table 2. Names for bacteria and bacterial groups used in this report and the corresponding obsolete forms.

Current Names	Obsolete Names
Phylogenic Groups	
Actinobacteria	High G+C Gram positive bacteria such as Actinomycetes, Mycobacterium, Rhodococcus
Eukaryotes	Fungi, protozoa, algae, flowering plants, and animals
Firmicutes	Low G+C Gram positive bacteria such as Bacillus and Clostridia
Proteobacteria	Gram-negative bacteria

Targeted Gene Detection

Specific DNA primers for a conserved region of the 16S rDNA gene were used to detect Dehalococcoides ethenogenes, based upon the method of Loffler et. al. (10). The sensitivity is ~10^3 cells per milliliter or gram of sample. Two amplification samples were used to ensure the validity of the results: negative control; E. coli and positive control; D. ethenogenes.

Results and Discussion

Phospholipid Fatty Acid Analysis

Biomass estimates (expressed as the total concentration of PLFA) were fairly similar in all three samples, however estimates were slightly higher in the samples collected downgradient (HAN-GW-RAP1-6T) and crossgradient (HAN-GW-1RZ1) of a molasses injection point (see Figure 1 and Table 3).

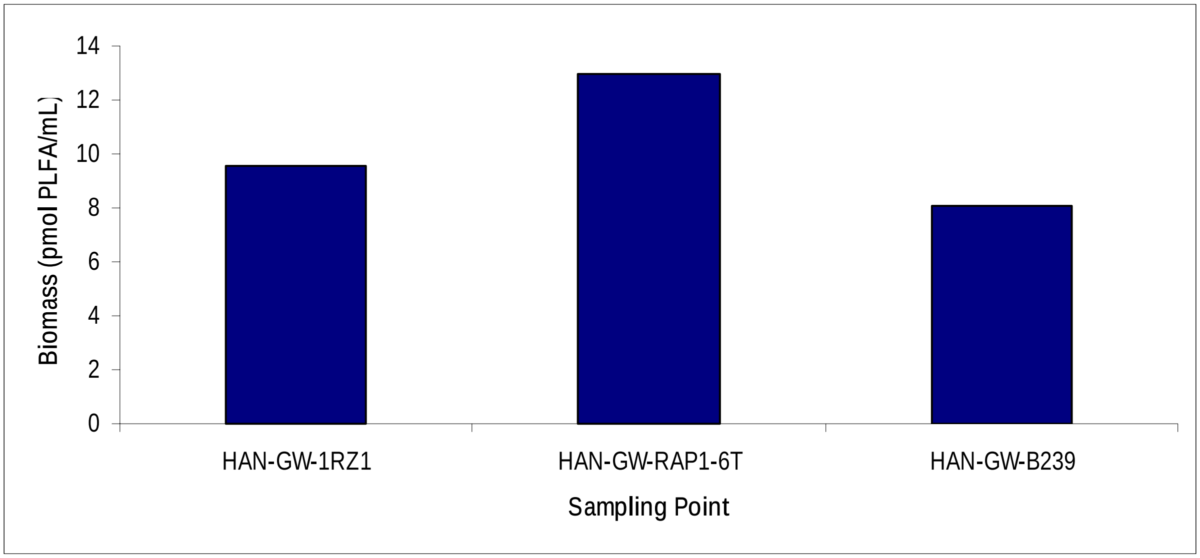


Figure 1. Biomass content is presented as the total amount of phospholipid fatty acids (PLFA) present in a given sample. PLFA comprise a large proportion of the membranes of all living cells, but decompose quickly upon cell death.

Table 3. Viable microbial biomass expressed as picomoles PLFA per mL and as cells per mL, fatty acid structural groups as percent of total PLFA, and physiological status biomarkers as mole ratio. "-" indicates data not available. Detection of Volatile fatty acids is expressed as mg/L. Results for the DHE amplification were performed using primers directed to a variable region of the 16S rRNA gene of *Dehalococcoides ethenogenes*. Presence is noted with a plus sign and the relative abundance determined by the number of plus signs.

Sample Name Sampling Date	HAN-GW-1R21 10/14/2002	HAN-GW-RAP1-6T 10/14/2002	HAN-GW-B239 10/14/2002
Biomass			
pmols PLFA/ml filtered	10	13	8
Cells/ml filtered[1]	1.91E+05	2.59E+05	1.61E+05
Community Structure: (% of Total PLFA)			
Firmicutes (TerBrSats)	17.2	16.6	9.9
Proteobacteria (Monos)	53.3	55.3	53.3
Anaerobic metal reducers (BrMonos)	2.4	2.7	3.9
Actinomycetes (MidBrSats)	3.2	2.2	6.1
General (Nsats)	22.5	20.8	19.5
Eukaryotes (polyenoics)	1.5	2.4	7.3
Physiological Status			
Starvation, Cy/cis	0.14	0.16	0.42
Membrane Stress, trans/cis	0.16	0.18	0.13
Volatile Fatty Acids (mg/L)			
Pyruvic	<4	<4	<4
Lactic	< 1	< 1	< 1
Formic	<1	<1	<1
Acetic	111	57	<1
Proprionic	18	6	<1
Butyric	14	7	< 1
Total VFA	143	70	ND
Dehalococcoides ethenogenes (DHE)			
Present/Absent	(Absent)*	Present (+++)	Present (+)

* No PCR product was obtained for either DNA analysis for this sample. Therefore, it is possible that DHE was present, but that we were unable to detect it because of PCR inhibiting compounds being present.

The PLFA profiles for these samples revealed relatively diverse community structures at all three sampling locations. All three communities were dominated by proteobacteria (indicated by percentage of monoenoic PLFA), which often rapidly reproduce to take advantage of available organic carbon. Terminally branched PLFA were higher in the samples collected downgradient (HAN-GW-RAP1-6T) and crossgradient (HAN-GW-1RZ1) of a molasses injection point. These are most commonly due to Firmicutes (clostridia-like Gram positive bacteria). An increase in terminally branched PLFA is often seen in environmental transects from more aerobic to more anaerobic conditions, so this may signal in increase in anaerobes (as compared to the upgradient location HAN-GW-B239) due to the injection of molasses (see Figure 2). Volatile fatty acids (VFA) were also

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[1] The cell equivalent value is calculated from experiments with typical bacteria isolated from soil and water. This value is based on 2.0 x 10^{12} cells per gram dry weight of cells and 10^{8} picomoles of phospholipid/gram dry weight of cells. The number of cells/gram of dry weight may vary and is dependent on the environmental conditions from which the microorganisms were recovered.

detected in the downgradient (HAN-GW-RAP1-6T) and crossgradient (HAN-GW-1RZ1) samples, which further indicates that conditions are anaerobic.

Physiological Status markers for starvation (cy/cis) showed that the Gram negative bacteria in the samples collected downgradient (HAN-GW-RAP1-6T) and crossgradient (HAN-GW-1RZ1) of a molasses injection point were less starved than those in the upgradient location HAN-GW-B239. This is likely a positive response from the molasses injection (see Figure 3).

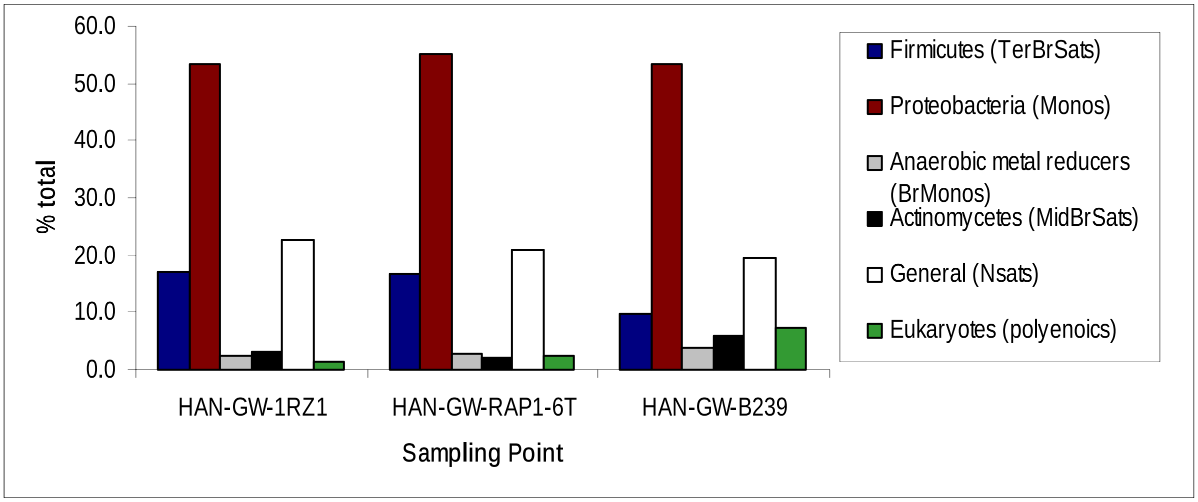

Figure 2. Relative percentages of total PLFA structural groups in the samples analyzed. Structural groups are assigned according to PLFA chemical structure, which is related to fatty acid biosynthesis. See Table 1 for detailed descriptions of structural groups. An "X" indicates samples with insufficient biomass for community structure to be determined.

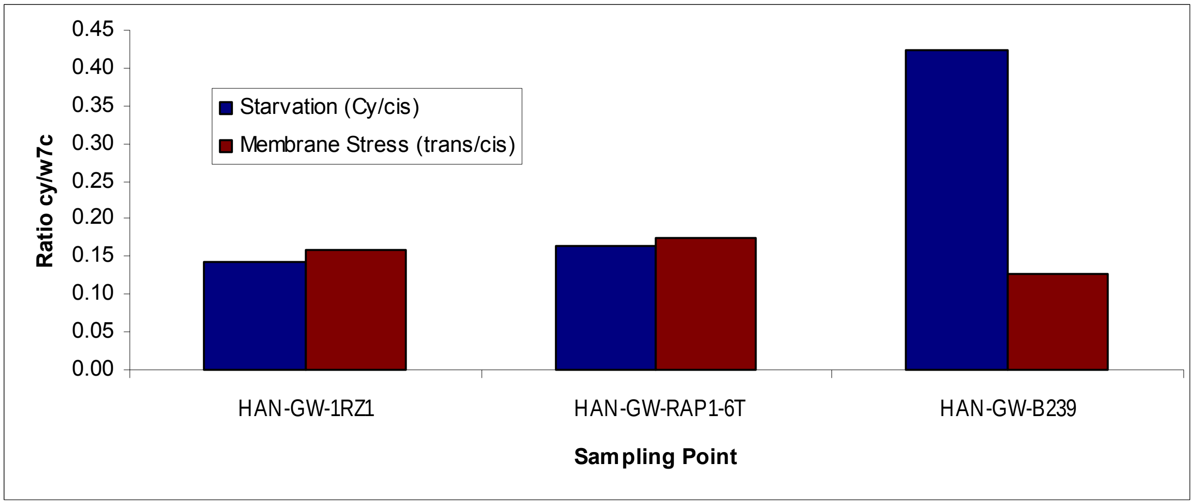

Figure 3. . Microbial physiological stress markers. Starvation biomarker for the Gram-negative community is assessed by the ratio cyclopropyl fatty acids to their metabolic precursor. Adaptation of the Gram-negative community to toxic stress is determined by the ratio of ω7t/ω7c fatty acids. Gram-negative bacteria generate *trans* fatty acids to minimize the permeability of their cellular membranes as adaptation to a more hostile environment. Ratios (16:1ω7t/16:1ω7c and 18:1ω7t/18:1ω7c) greater than 0.1 have been shown to indicate an adaptation to a toxic or stressful environment resulting in decreased membrane permeability. An "X" indicates samples with insufficient biomass for metabolic status markers to be determined.

Denaturing gradient gel electrophoresis (DGGE)

DGGE profiles were only obtained from samples HAN-GW-RAP1-6T and HAN-GW-B239. It is likely some type of inhibition made it difficult to obtain DNA results from HAN-GW-IRZ1. Only the bacterial profile for sample HAN-GW-RAP1-6T produced a distinct banding pattern in which identifications could be obtained. These results identified three anaerobic bacteria, two Bacteriodes, and a Clostridium. Members of the genus bacteriodes are obligate anaerobic Gram negative bacteria, which produce high levels of acetate and succinate as metabolic end products. Information about the presence bacteria affiliated with *Bacteriodes* at contaminated sties is limited, but does indicate conditions are anaerobic. Members of the genus *Clostridium* are anaerobic counterparts to the Bacilli. Some members of this genus are notable pathogens, but other members can be found in environmental samples where oxygen is absent (or at least restricted where they are growing). Clostridia are commonly found in soils, sewage, marine sediments, and decaying vegetation. As a group, they have a wide pH tolerance range (4.5 – 8.5), can use a variety of compounds as energy sources, and form drought- and oxygen-resistant spores. Some Clostridia can fix nitrogen, taking nitrogen gas (N_2) to form ammonium. While there have been some recent publications (see appendix) suggesting the involvement of *Clostridium bifermentans* in the dehalogenation of PCE, a review article published in 1999 in Bioremediation Journal listed several members of *Clostridium* that were unable to dechlorinate PCE.

Given the limited information obtained from the DGGE profiles, a targeted gene detection for a known dechlorinating bacterium, *Dehalococcoides ethenogenes* (DHE), was used to determine its presence. Bacteria belonging to the *Dehalococcoides* assemblage are currently the only known organisms capable of converting all chlorinated ethenes to ethene. Given this, detection of this organism provides insight into the genetic potential of a given site. Within these three samples, DHE was detected in HAN-GW-RAP1-6T and HAN-GW-B239. The presence of DHE in HAN-GW-IRZ1 is inconclusive at this point given the difficulty with amplification.

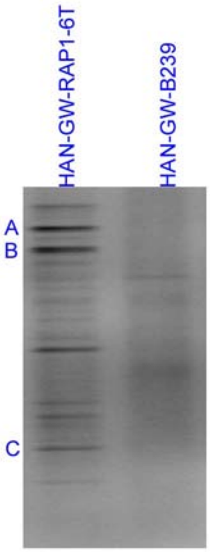

Figure 4. DGGE gel image of the bacterial domain. Banding patterns and relative intensities of the recovered bands provide a measure of change in the community. Dominant species must constitute at least 1-2% of the total bacterial community to form a visible band. Labeled bands were excised and sequenced. Results from sequencing can be found in the following table.

Table 4. Sequence results from bands excised from Figure 5. Identifications are based upon the Ribosomal Database Project (RDP). Similarity indecies above .800 are considered excellent, .600-.700 are good and below .500 are considered to be unique sequences.

Band	Closest Match	Similarity Index	Phylogenetic Affiliation	Habitat	Ref
A	Uncultured Bacteriodes sp.	0.865	Bacteriodetes	Anaerobic	-
B	Uncultured Bacteriodes sp.	0.865	Bacteriodetes	Anaerobic	-
C	Clostridium sp.	0.995	Firmicutes	Anaerobic	-

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Appendix C

Quality Assurance Project Plan (QAPP)

This QAPP (Appendix C) was taken from the following document:

Technology Demonstration Plan
Hanscom Air Force Base

TECHNOLOGY DEMONSTRATION *IN-SITU* SUBSTRATE ADDITION TO CREATE REACTIVE ZONES FOR TREATMENT OF CHLORINATED ALPHATIC HYDROCARBONS

Prepared by:

ARCADIS Geraghty & Miller, Inc.
P.O. Box 13109
Research Triangle Park, NC 27709

March 2, 2000

Table of Contents

9. Quality Assurance Plan

9.1 Purpose and Scope of the Plan

This QA Plan delineates our approach for monitoring the demonstration to ensure that the facilities, equipment, personnel, methods, practices, records, and controls are in conformance with ESTCP-approved data quality objectives. In addition to preparing this QAPP, ARCADIS Geraghty & Miller's Research Triangle Park Office, the lead office for this project, operates under a quality system that is described in an office Quality Management Plan written according to ANSI/ASQC E4-1994 *Specifications and Guidelines for Quality Systems for Environmental Data Collection and Environmental Technology Programs.*

9.2 Quality Assurance Responsibilities

The ARCADIS Geraghty & Miller Program Manager/Principal Investigator has the following QA responsibilities:

- Review Demonstration QA Project Plan, Sampling Plans, Test Plans, etc.
- Serve as the project's liaison with senior corporate management to ensure the assignment of adequate resources
- Review decisions about major corrective actions
- Review Final Report and Cost & Performance Report
- Serve as the primary quality assurance reviewer and authority for engineering design and geologic matters. Will be assisted in this regard by personnel licensed in states where Mr. Palmer is not licensed

The ARCADIS Geraghty & Miller Project Manager has the following QA responsibilities:

- Coordinate preparation of Demonstration QA Project Plan, Sampling Plans, Test Plans, etc.
- Ensure personnel assigned to project are adequately trained
- Ensure activities are carried out as planned and deviations are documented
- Ensure equipment and instrumentation is calibrated and in good working condition
- Initiate corrective action procedures
- Communicate any problems or deviations from plan to the QA Officer
- Coordinate preparation of Final Report and Cost & Performance Report

The ARCADIS Geraghty & Miller QA Officer for this demonstration has the following responsibilities:

- Review and approve Demonstration QA Project Plan, Sampling Plans, Test Plans, etc.
- Perform periodic audits to ensure demonstration is conducted as planned and any deviations from plan or standard methods are adequately documented
- Report any audit findings or problems to the Project Manager
- Review laboratory data and ensure it is supported by appropriate QA/QC information
- Review Final Report and Cost & Performance Report to ensure that is accurately describes the methods and standard operating procedures, and that the reported results are supported by raw data

It is the responsibility of the Project Manager and Deputy Project Manager to ensure that required QA/QC documentation is in place before any demonstration activity is begun and that documented QA/QC activities are carried out in all phases of the demonstration. Christopher Lutes is the Project Manger and Don Kidd is the Deputy Project Manager for this demonstration. Project Management is responsible for ensuring that staff members are adequately trained to perform assigned duties.

Ms. Laura Beach is the Data Quality Assurance Officer for the IRZ demonstration. Ms. Beach is the QA Manager for ARCADIS Geraghty & Miller's Technology Services Division. She has more than 10 years of experience in providing QA support to government contracts (for example, USEPA-APPCD, USEPA Environmental Technology Verification Program, NFESC Innovative Technology Project and USAF Environics Directorate Support) and is very familiar with the QA/QC activities required to support them. The Data Quality Assurance Officer will assume responsibility for, or assign an on-site QA representative to perform QA support activities during the demonstration. Any designated QA representative will report regularly to Ms. Beach and will be jointly responsible for ensuring that QA tasks meet contractual requirements as well as the requirements that are established in the ARCADIS Geraghty & Miller Raleigh RTP Office Quality Management Plan referenced earlier. The Data Quality Assurance Officer's responsibilities include support in the preparation and review of this work plan, conducting internal systems and/or performance audits, QA/QC reporting, and involvement in the correction of any issues leading to data quality concerns.

As Project Managers, Mr. Lutes and Mr. Kidd will openly communicate with both Ms. Beach and the senior project advisors. The assigned Engineering and Biogeochemical Assessment Team Leaders for the IRZ demonstration are Mike Hansen and Jeffrey Burdick respectively. Project personnel including both Team Leaders, other technical staff, and field technicians are expected to work closely with the Data Quality Assurance Officer to ensure that QA/QC activities are adequate and that any problems are identified and corrected. Corrective actions are initiated by the Team Leader Project Manager and reported to both the Principal Investigator and the Data Quality Assurance Officer.

It is the intention of ARCADIS Geraghty & Miller that communications about data quality flow freely both up and down the organizational chart during the demonstration. Past experience in ARCADIS Geraghty & Miller suggests that it is imperative to include field level personnel in communications pertinent to data quality. This open communication to and from field staff will aid in ascertaining the quality of the data generated during the effort.

9.3 Data Quality Parameters

Table 6 contains goals for the data quality parameters accuracy, precision, and completeness for the analytical measurement process. The table incorporates data quality goals for field analysis (temperature, ORP, pH, and dissolved oxygen) and for fixed laboratory based analysis. Thus, this table has been compiled with input from ARCADIS Geraghty & Miller as well as from the two analytical laboratories that will conduct laboratory based analyses for analytes stable enough to be shipped.

ARCADIS Geraghty & Miller and its subcontract analytical laboratories will rely primarily on timely servicing and appropriate calibration of analytical instruments to attain the accuracy goals listed in Table 6. With the possible exception of hydrogen analysis, the analyte list contains parameters that have been chemically quantified for many years in environmental media. As a result, correctly performed analysis of these parameters is capable of generating the accuracy needed to guarantee the success of this demonstration.

It is important to attain the accuracy goals contained in Table 6 for the listed analytes so as to facilitate inter-comparison of analytical results from multiple collection points at individual demonstration sites. The IRZ technology is expected to affect/generate trends in the analytes listed in Table 6 within each reactive zone. The trends generated by molasses injection are important in determining the size and bacterial community characteristics of the reactive zone over time.

ARCADIS Geraghty & Miller routinely checks the precision of its analytical field instruments as a course of collecting data during low flow well sampling activities. The procedure universally utilized is to purge the well being sampled and then begin pumping the groundwater through a low-flow, flow-through sample cell where it comes into contact with probes that are calibrated for the parameters of interest. The groundwater is pumped through the sample cell until the readings for the parameters of interest stabilize with the precision guidelines found in Table 6. Thus, precision is determined at the completion of the period required for the parameter readings to stabilize. Likewise, the contract analytical laboratories chosen for this project are accustomed to goals similar to those shown in Table 6. Accuracy, Precision, and Completeness Goals for Analytical Parameters routinely determining the precision of their analyses in keeping with their commitment to quality control.

Representativeness of groundwater samples is assured by careful well placement and through purging of each well prior to sample collection. ARCADIS Geraghty & Miller's assessment of site geology and hydrogeology is essential to verification of appropriate well placement. ARCADIS Geraghty & Miller has commenced this assessment using available data from individual site characterization efforts and will complete the effort in the course of establishing initial site conditions during the first round of biogeochemical analyses. The purging of groundwater wells is a part of the sampling procedures to be utilized at the demonstration sites. Purging of the wells insures that the chemical properties of the groundwater collected for analysis has not altered as a function of residence time within the well casing itself.

The use of identical analytical methodologies during the conduct of work at four demonstration sites will support the comparability of the data gathered during this project. This standardization of analytical methods is important so that the economics of IRZ implementation at the four sites can be delineated and reported to ESTCP/AFCEE.

9.4 Calibration Procedures, Quality Control Checks, and Corrective Action

Calibration procedures for the standard EPA and ASTM methods are covered fully in those methods. Copies of the methods are available upon request.

9.4.1 Dissolved Gas Methods – Fixed Facilities. The dissolved gas methods referred to above are provided in full Appendix B. In short the light hydrocarbon method calls for a three point external calibration with calibration standards prepared from commercial certified gas standards traceable to the National Institute of Standards of Technology standards. The carbon dioxide method uses triplicate external calibration points with calibration standards prepared from commercially available certified gas standards traceable to National Institute of Standards of Technology standards. The hydrogen method uses a 7 point external calibration with calibration standards prepared from commercial certified gas standards. The laboratory data package provided by VaporTech includes initial calibration, continuing calibration check results (control limit is +/-20%), case narrative, chain of custody and laboratory blank results. Their are no established holding times for these analyses. Vapor Tech uses the 7 day VOA unpreserved holding time for the light hydrocarbons and carbon dioxide, and has demonstrated the adequacy of a 28 day holding times for hydrogen. Since the calibration is performed with gas standards, and analyses from liquid samples, it is generally not possible for Vapor Tech to report laboratory control spikes or matrix spikes. Vapor Tech will provide Excel compatible electronic deliverables which can be directly used by ARCADIS Geraghty & Miller to prepare final data tables following validation.

9.4.2 Chemical Fixed Facility Measurements. Quanterra's QC protocols include the following:

- Minimum of one method blank is analyzed per 20 samples to detect contamination during preparation and/or analysis
- Laboratory Control Sample (LCS) consisting of target analytes spiked into a inert matrix is analyzed every 20 or fewer investigative samples. The LCS is used to monitor the laboratory's day to day as well as ongoing performance of the applicable analytical methods
- Matrix spikes and matrix spike duplicates (MS/MSD) for organic analyses and matrix spikes and matrix duplicates (MS/DU) or MS/SD's for inorganic analyses will be analyzed every 20 or fewer samples to determine the affect of the matrix on the method performed. Due to the potential variability of the matrix, the MS/SD results may have bearing on the specific sample spiked and not all samples in the batch
- Internal and surrogate standards will be added where appropriate to quantitate results, determine recoveries and to account for sample-to-sample variation

Calibration of instrumentation will be determined according to the appropriate EPA methods.

The Quanterra data reports will contain the following items:

1. Case Narrative
    a. Date of issuance
    b. Laboratory analysis performed
    c. Any deviations from intended analytical strategy
    d. Laboratory batch number
    e. Numbers of samples and respective matrices
    f. Quality control procedures utilized and references to the acceptance criteria
    g. Laboratory report contents
    h. Project name and number
    i. Condition of samples received
    j. Discussion of whether or not sample holding times were met
    k. Discussion of technical problems
    l. Signature of Laboratory Project Manager

2. Chemistry Data Package
    a. Case narrative for each analyzed batch of samples
    b. Cross reference of laboratory sample to project sample identification numbers
    c. Sample results with sample preparation and analysis dates
    d. Raw data for sample results and laboratory quality control samples

e. Initial and continuing calibration checks, GC/MS tunes
f. Matrix spike and matrix spike duplicate recoveries, laboratory control samples, method blank results, calibration check compounds, system performance check compounds
g. Labeled and dated chromatograms and spectra of sample results and laboratory quality control checks

The data package will include a full CLP-like deliverable package without CLP forms.

Quanterra will provide an ASCII comma delimited electronic deliverable.

9.4.3 Geotechnical Fixed Facility Measurement. Calibration procedures for the ASTM particle size methods are included in the method. Essentially the only required calibration is on a balance. The balance calibration will be reported with that data set. The sieve screens are ‘calibrated’ by the manufacturer and inspected by the laboratory for tears before use.

9.4.4 Field Measurements. Calibration procedures for field instruments are included in Appendix E ARCADIS Geraghty & Miller field instrument standard operating procedures manual.

9.4.5 Data Validation. Formal validation will be performed on measurements of the contaminants but only a rapid review of data quality indicators will be performed for the other biogeochemical parameters. Site by site final reports and a cost and performance report will be prepared in accordance with ESTCP formats. It is anticipated that these reports will include both tabular and graphical depictions of the data collected.

9.5 Demonstration Procedures

9.5.1 Start-up. Start-up activities for the demonstration will be limited. Initiation of the demonstration will begin with the collection of the baseline groundwater monitoring data (as outlined in section 5.4). This will be followed by the initial reagent solution injection in the injection well network. Upon completion of the baseline data collection and initial reagent injection the demonstration will move into the technology maintenance phase.

9.5.2 Technology Maintenance. Please see section 5.3.9.

9.5.3 Corrective Actions. Corrective action with regard to analytical measurements has been discussed in section 6.1. Corrective action with regard to system operation is covered in section 5.3.8.

9.6 Calculation of Data Quality Indicators

Accuracy: Accuracy can be expressed as percent bias from a known standard or percent recovery based upon known spiked amounts. Percent bias is calculated using the following equation:

$$\%\text{Bias} = [\text{known value} - \text{obtained value})/\text{known value}] * 100$$

Percent recovery is calculated by:

$$\%\text{Recovery} = [\text{measured value}/\text{spiked amount}] * 100$$

Precision: Precision, expressed as relative standard deviation (RSD) between replicate measurements can be determined using the formula:

$$\%\text{RSD} = \text{standard deviation of replicate measurements}/\text{average} * 100$$

Completeness: Completeness is defined as the number of acceptable measurements compared to the number of total measurements taken expressed as percent. Acceptable measurements are defined as measurements that fall within data quality indicator goals for accuracy and precision.

Comparability and Representativeness: Comparability is defined as the degree to which different methods, data sets, and/or decisions agree or can be represented as similar. The methods used to obtain data and the manner in which data is presented will be consistent throughout this program to ensure comparability between data sets.

Representativeness is defined as the degree to which data accurately and precisely represent the frequency distribution of a specific variable in the population. A great deal of thought will be spent by the Principal Investigators at each site to ensure that the data obtained is representative. Issues that will be assessed are the number and location of wells with regard to the plume at each site, the number of samples taken, and the analytes present at each site.

9.7 Performance and System Audits

9.7.1 Performance and Systems Audits. The ARCADIS Geraghty & Miller QA Officer, or her designee, routinely performs audits to ensure that projects are performed according to plan and that acquired environmental data is of a known and defensible quality. Audits performed by ARCADIS Geraghty & Miller on ARCADIS Geraghty & Miller projects are considered internal audits. Audits performed by a third party or by EPA are considered external audits.

An internal technical systems audit (TSA) for at least one site will be performed during the early stages of this demonstration. The QA Officer will use this QA Project Plan as a basis for the TSA checklist, in addition to the standard methods used for sampling and analysis. The purpose of the technical systems audit is to ensure that the project is carried out as planned and that any deviations from the methods or plan are adequately documented. To reduce costs, the QA Officer may assign a Deputy QA Officer from an office located in close proximity to the sampling site to perform the field audit of sampling procedures. This Deputy QA Officer will be independent of the project and technically qualified to carry out this duty.

Analytical activities may be audited by providing the subcontracted laboratories with a performance evaluation audit (PEA) sample. The laboratories that are being used are routinely audited under EPA's contract laboratory program and through ARCADIS Geraghty & Miller's internal laboratory approval program. The date and results from the last audit performed at each laboratory will be requested. If they have not been audited within the last year, by EPA or ARCADIS Geraghty & Miller, analysis of PEA samples supplied blind by the ARCADIS Geraghty & Miller QA Officer will be required.

9.7.2 Contingency Laboratory. During the competitive bidding process discussed above contingency laboratories were identified. STL and IES can serve as contingency labs in case Quanterra is unable to perform. Microseeps can serve as a contingency laboratory in case vapor Tech is unable to perform. ARCADIS Geraghty & Miller can perform the particle size analysis in its own facility if WEA is unable to perform.

9.8 Quality Assurance Reports

Quality related problems will be addressed in monthly progress reports prepared by the Project Manager if data quality is compromised. Reports will detail any limitations on the data and any corrective actions that were implemented to resolve the problem.

Any findings, problems, or observations found through internal audits by the QA Officer will be reported directly to the Project Manager. Major concerns will be expressed on the day of the audit if immediate corrective actions are necessary. The QA Officer will submit an audit report to the Project Manager within 15 days of completion of any internal audit.

The final report for each site will contain a QA section that will specify the QA activities that were conducted at the site and the quality of data achieved. It will provide sufficient information to enable users to have confidence in the data. If the data have limitations, the QA section will detail those limitations. The QA section of the final report will also relate data to the established data quality objectives and data quality indicator goals and explain any significant differences.

It is anticipated that significant quality assurance issues will be discussed in monthly status reports and quarterly performance and cost reports as well as annual presentations. Therefore interested parties will be aware of these issues if any arise before completion of the final report.