ESTCP
Cost and Performance Report

(ER-9920)

In-situ Substrate Addition to Create Reactive Zones for Treatment of Chlorinated Aliphatic Hydrocarbons

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ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

COST & PERFORMANCE REPORT
ESTCP Project: ER-9920

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ACRONYMS AND ABBREVIATIONS

μg/L	micrograms per liter
AAP	Army Ammunition Plant
AFB	Air Force Base
AFCEE	Air Force Center for Environmental Excellence
AHTNA/ACOE	AHTNA Government Services Inc, Army Corps of Engineers
AOC	area of concern
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
cis-DCE	cis-1,2-dichloroethene
COC	constituents of concern
COD	chemical oxygen demand
CT	carbon tetrachloride
CTC	cost-to-complete
DCE	dichloroethene
DERP	Defense Environmental Restoration Program
DGGE	denaturing gel electrophoresis
DNAPL	dense, non-aqueous phase liquid
DO	dissolved oxygen
DOC	dissolved organic carbon
DoD	Department of Defense
EARP	enhanced anaerobic reductive precipitation
EPA	Environmental Protection Agency
ERD	enhanced reductive dechlorination
ESTCP	Environmental Security Technology Certification Program
FRTR	Federal Remediation Technologies Roundtable
GC	gas chromatograph
GFPR	guaranteed, fixed-price remediation
HAZWOPER	hazardous waste operations and emergency response
HRTW	Hazardous, Toxic and Radioactive Waste
IRM	interim remedial measure
IRZ	in situ reactive zone
K	hydraulic conductivity

MCL	maximum contaminant level
mg/L	milligrams per liter
MNA	monitored natural attenuation
NPL	National Priorities List
NPV	net present value
O&M	operation and maintenance
ORP	oxidation reduction potential
OU	Operable Unit
OU1	Operable Unit 1
PBC	performance based contract
PCE	tetrachloroethene
PLFA	phospholipid fatty acid
psig	pounds per square inch gauge
QA/QC	quality assurance/quality control
QAPP	Quality Assurance Project Plan
RCF	revised cost format
RCRA	Resource Conservation and Recovery Act
SERDP	Strategic Environmental Research and Development Program
SOP	standard operating procedure
STL	Severn Trent Laboratories
s.u.	standard units
TCE	trichloroethene
TCRAS	time critical removal action
TDS	total dissolved solids
TOC	total organic carbon
trans-DCE	trans-1,2-Dichloroethene
UIC	underground injection control
U	uranium
VAFB	Vandenberg Air force Base
VC	vinyl chloride
VER	vacuum-enhanced recovery
VOA	volatile organic analysis
VOC	volatile organic compound
WBS	work breakdown structure

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Technical material contained in this report has been approved for public release.

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1.0 EXECUTIVE SUMMARY

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 chlorinated aliphatic hydrocarbons (CAH) such as carbon tetrachloride, methylene chloride, trichloroethane, trichloroethene (TCE) and tetrachloroethene. In addition to their roles in many industrial processes, CAHs have been used extensively for cleaning and degreasing. The U.S. Armed Forces are faced with widespread, costly remediation problems related to these compounds.

The conventional remedies for CAH contamination in groundwater are groundwater extraction and ex situ treatment, also known as pump and treat, or in situ air sparging. An alternative approach is anaerobic in situ reactive zone (IRZ) technology for the remediation of CAHs and metals. Anaerobic IRZ technology involves the addition of a food grade, soluble carbohydrate substrate, which serves as a supplemental energy source for microbiological processes in the subsurface. The substrate is typically molasses, but other substrates can be used, including high fructose corn syrup, whey, etc. Through subsurface carbohydrate injection, 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. This technology is more specifically referred to as enhanced reductive dechlorination (ERD) for CAHs or enhanced anaerobic reductive precipitation (EARP) for metals.

The primary benefits of ERD technology include its ease of regulatory acceptance, its in situ nature and its relatively low cost. Benefits of ERD technology include its record of successful application at various constituent concentrations, in varied geologies, and under multiple regulatory programs.

The subject IRZ demonstrations consisted of small, field-scale pilot tests at two sites with TCE plumes: Hanscom Air Force Base (AFB) in Massachusetts and Vandenberg AFB in California. The Hanscom pilot made use of one injection well, and the Vandenberg pilot used three injection wells, both with an array of monitoring wells. Both systems were operated manually by batch feeding molasses solutions from a trailer-mounted tank. Monitoring wells were sampled for a comprehensive list of process monitoring and effectiveness monitoring parameters.

1.2 OBJECTIVES OF THE DEMONSTRATION

The objectives of the demonstrations were to demonstrate the ability to remediate contaminants in the subsurface over a relatively short time period and to gather information for estimating long-term treatment effectiveness, life span, and costs. The results of the demonstrations were used to develop a protocol using ERD technology at Department of Defense (DoD) facilities (Suthersan, 2002). Also important in these demonstrations was to show that the degradation of CAHs does not “dead-end” at undesirable by-products such as cis-1,2-dichloroethene (cis-DCE) and vinyl chloride (VC).

1.3 REGULATORY DRIVERS

Groundwater impacts by CAHs at DoD sites are regulated under the Resource Conservation and Recovery Act (RCRA) and Comprehensive Environmental Response Compensation and Liability Act (CERCLA) (Superfund) programs as well as state regulatory programs. Cleanup goals for groundwater are often U.S. EPA maximum contaminant levels (MCL) for drinking water, unless an alternate, negotiated cleanup goal is established. Hanscom AFB is a CERCLA site, regulated by the EPA. The long-term cleanup goal for the Hanscom site is to achieve drinking water standards, in this case, federal MCLs. The Vandenberg AFB site is overseen by state agencies in California under a Federal Facilities Site Remediation Agreement. In the absence of a negotiated cleanup goal at this site, the default primary goal is MCLs. The demonstration plans described a strategy for achieving risk-based site closure by coupling an active remedy using ERD for concentration reduction with natural attenuation as a polishing step.

1.4 DEMONSTRATION RESULTS

During the 2 years of active treatment at Hanscom, highly effective, complete TCE and dichloroethene (DCE) removal was demonstrated in a source area that had a long history of fairly stable TCE concentrations before treatment. Evidence of complete treatment—reduction in cis-DCE, no accumulation of VC, substantial reduction of VC, and a buildup of ethene—was also seen in the most effectively treated downgradient wells. Unexpected variability in the groundwater flow direction resulted in inconsistent distribution of the carbohydrate substrate, and effective treatment was seen only where substantial substrate was observed in downgradient monitoring wells. No rebound of CAH concentrations had occurred as late as 17 months after the last injection; rather, effective treatment appeared to be continuing (see the Environmental Security Technology Certification Program [ESTCP] website for a supplemental report of Hanscom rebound data). Furthermore, the demonstration area was in a source zone; thus long-term effectiveness in a source zone was observed.

The Vandenberg demonstration was initially hampered by the low buffering capacity of the aquifer, which caused pH to be depressed to levels below the desired operating range. However, after a buffer was implemented, more reagent was delivered, and system performance improved. Although the quantitative goal of 80% reduction in total CAHs within 1 year was not attained, reductions in TCE concentrations were $\geq$ 80% at the most highly treated monitoring wells 27 months after treatment began. Effective treatment of CAHs continued at most of the reactive zone wells after the last injection, and in some cases was even enhanced by recovering pH levels. No rebound in CAH concentrations was seen as of 16 months after active treatment (see a separate report of rebound period monitoring at Vandenberg on the ESTCP website). Substantial differences were noted in the reagent distribution characteristics of the three injection wells used.

1.5 COST ASSESSMENT

Actual demonstration costs were used to extrapolate an estimated cost for a hypothetical full-scale system at Hanscom AFB of $3.6 million. This was compared to an estimated life-cycle cost for the existing pump-and-treat system at Hanscom of $22.3 million. Although there is considerable uncertainty associated with both estimates, it appears that ERD technology would be much more economical than the pump-and-treat remedy. For other ERD applications, actual project costs have ranged from approximately $75,000 to $2 million, representing sites of varying scales and complexity.

The two most costly elements of ERD implementation are injection well installation and operation and maintenance (O&M) associated with reagent injections. Significant variables are the size of the plume to be treated, the depth of the target zone, the rate of groundwater flux through the treatment zone, and monitoring requirements. The estimate for the hypothetical full-scale system at Hanscom was found to be sensitive to the period of injection and more so to well spacing (number of injection wells used).

The technology has been widely used at full scale at DoD sites. Assuming that the use of ERD would produce an average 50% cost savings over pump and treat and that ERD would be appropriate for half of DoD's groundwater CAH sites, it is estimated that the savings to DoD from application of ERD would be $626 million.

1.6 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 production of gases, intermediate products of dechlorination and secondary water quality impacts from ERD applications is expected within the reactive zone and is also of potential concern to stakeholders and regulatory agencies. Adaptive design and operations approaches are needed to allow full-scale system operators to manage groundwater flow direction and velocity changes. None of these issues should be considered major impediments to technology implementation but must be considered in the design of each project. Secondary water quality impacts (including metals mobilization, high chemical oxygen demand [COD]/biochemical oxygen demand [BOD], and ketones) were observed at the demonstration sites, but as expected were limited to the areas of the reactive zones and did not appear to be significant downgradient. A potential end user issue is that the reducing conditions induced by substrate injections persisted, at least at Hanscom, for a substantial period. Although this could be a benefit in cases where long-lasting treatment is desired, it could also be a detriment in cases where the groundwater within the reactive zone needs to return rapidly to aerobic conditions to support a planned immediate use.

The ERD technology was developed primarily in the private sector and has been applied at numerous sites. These sites involved regulators and a variety of site conditions in different geographic areas of the country. The technology is mature as a plume remediation strategy or barrier strategy. Issuance of the protocol entitled "Technical Protocol for Using Soluble Carbohydrates to Enhance Reductive Dechlorination of Chlorinated Aliphatic Hydrocarbons" (published on a Strategic Environmental Research and Development Program [SERDP]/ESTCP website) is a major technology transfer step. The results of the demonstration have also been presented as case histories in publications and at numerous conferences attended by DoD staff.

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2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

Enhanced reductive dechlorination (ERD) technology is intended to facilitate and expedite the biological reductive dechlorination of chlorinated aliphatic hydrocarbons (CAH) through the well-documented pathways pictured in Figure 1. The ERD technology stimulates indigenous microbiological organisms through the engineered addition of electron donors, which contain degradable organic carbon sources.

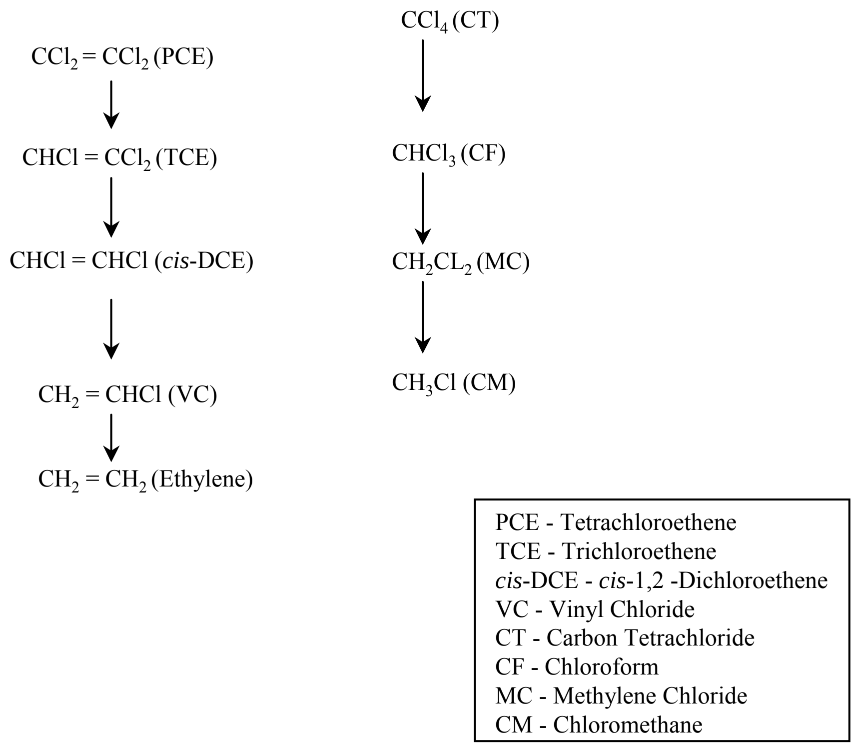


Figure 1. Anaerobic Transformations of Selected CAHs and Their Daughter Products
(Vogel et al, 1987 and McCarty and Semprini, 1993).

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 consisting of a carbohydrate such as molasses, whey, high fructose corn syrup, lactate, butyrate, or benzoate. The 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 by biological reductive dechlorination and certain abiotic reactions. 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. 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 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. Figure 2 provides a conceptual design of this process has been provided as Figure 2. This technology can be implemented in a variety of ways, including fixed, automated systems and mobile, manually controlled systems. These systems can be used for source area treatment, dissolved phase plume treatment or in a barrier mode. The particular system used in this demonstration, at both sites, was truck-mounted (see Figure 3 for a schematic and Figure 4 for a photograph of this system).

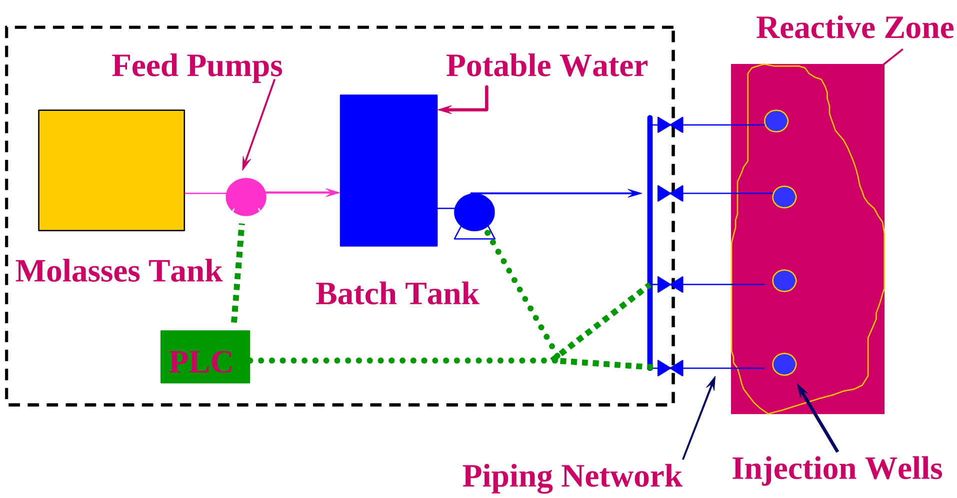
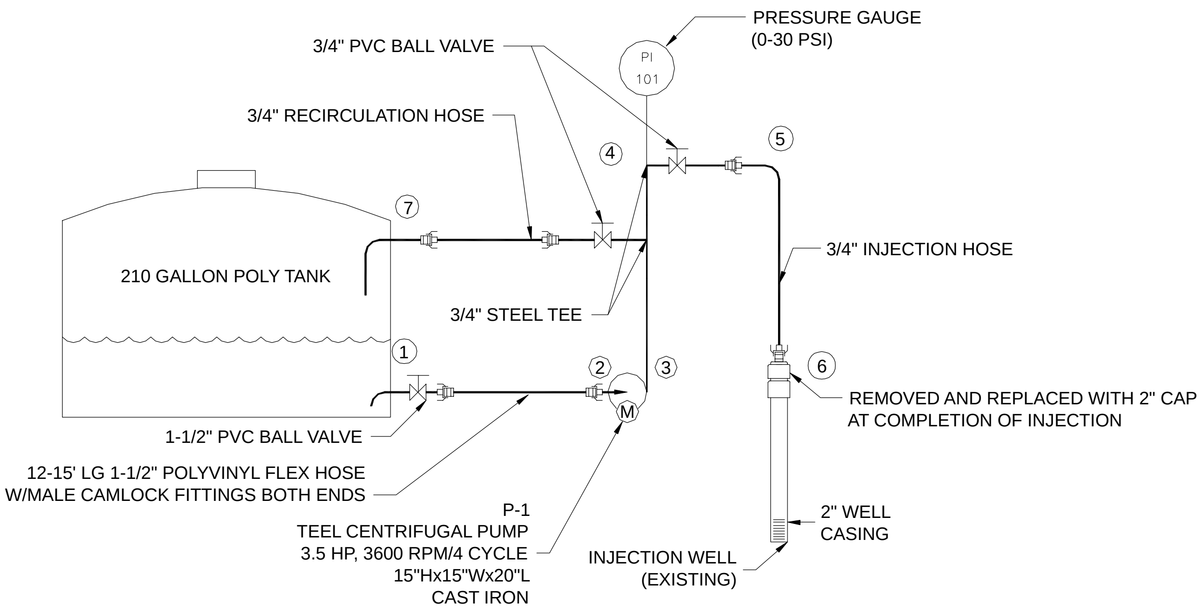


Figure 2. Conceptual Design for an ERD System Layout.

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.

Since 1994, in situ reactive zone (IRZ) applications have demonstrated the effectiveness of ERD for remediation of CAHs and other contaminants. 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 continues to improve the design and optimize performance of ERD systems under varying conditions.



ZONE	COMPONENT DETAILS
1	90 DEG PVC ELBOW (INSIDE TANK) 2" PVC TANK ADAPTER PVC REDUCER 2" - 1 1/2" (OUTSIDE TANK) 1-1/2" PVC BALL VALVE 1-1/2" FEMALE CAMLOCK FITTING
2	1-1/2" FEMALE CAMLOCK 1-1/2" STEEL NIPPLE/ UNION (INLET CONNECTION TO PUMP)
3	1-1/2" STEEL NIPPLE / UNION (OUTLET CONNECTION TO PUMP) 1-1/2 - 3/4" STEEL REDUCER 3/4" STEEL NIPPLE
4	3/4" STEEL TEE LIQUID FILLED PRESSURE GAUGE
5	3/4" MALE CAMLOCK FITTING 3/4" (150 PSI) SWAN CONTRACTOR WATER HOSE (~25' LONG) WITH 3/4" FEMALE CAMLOCK FITTINGS AT BOTH ENDS
6	2" PVC COUPLING SLIP TO MP 2" PVC COUPLING 3/4 X 2" REDUCER 3/4" MALE CAMLOCK
7	3/4" PVC TANK ADAPTER 3/4" MALE CAMLOCK FITTING 3/4" (150 PSI) SWAN CONTRACTOR WATER HOSE (~25' LONG) WITH 3/4" FEMALE CAMLOCK FITTINGS AT BOTH ENDS

Figure 3. Reagent Mixing and Injection System Schematic—Vandenberg Air Force Base (VAFB).

Figure 4. Reagent Mixing and Injection System Photograph—HAFB.

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

- Chlorinated cyclic hydrocarbons, e.g., pentachlorophenol
- 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
- Radionuclides such as uranium (U).

2.2 PROCESS DESCRIPTION

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

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

Ultimate design goals include contaminant removal rates and closure requirements. Interim design goals are set to ensure the creation of appropriate conditions for CAH biodegradation and typically include optimal ranges for field parameters and total organic compound (TOC).

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

- Substrate to be used and initial dosing 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 versus automated, conventional well versus direct push, etc.)
- Systems to handle by-products (which may include injecting buffers or using venting systems under structures).

Pilot testing is usually required to establish distribution and engineering characteristics and critical adjustment or "tuning" of the system during operation.

Equipment required for technology implementation as applied at Hanscom and Vandenberg was nonspecialized 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 ERD are available commercially off the shelf and through subcontract with laboratories, drilling contractors, etc. ERD technology is relatively easy to implement beyond the design phase and should generally require only environmental technicians for field implementation and maintenance. Automated systems and those involving extraction or reinjection systems require custom design; the ease of implementing such systems is design-dependent.

Physical setup for a manual injection system is minimal. Permanent equipment is limited to wells with removable well seals with fittings on the injection wells to allow for connection. Utility requirements are limited to a source of potable water for mixing the molasses solution.

Temporary equipment required for injections typically includes the following: a 210-gal solution mixing/holding tank, a gasoline powered transfer pump, and an injection hose. Temporary equipment, carbohydrates, and other additives (tracer, buffer), may be stored in an on-site building. A conventional pick-up truck may be used to transport the equipment to the injection well for each injection event.

Safety issues are limited to those associated with handling equipment (vehicles, pumps, hoses, and fittings) in the field, and working with contaminated groundwater from wells. No hazardous materials are used in the injection solution. Appropriate precautions should be taken to manage purge water from well sampling and the potential for gas generation (Suthersan et al, 2002).

2.3 PREVIOUS TESTING OF THE TECHNOLOGY

As of April 2005, ARCADIS has been involved with more than 175 ERD sites in eight countries and 32 U.S. states. More 50 of these sites are full-scale implementations, six of which have achieved closure. The other sites are ongoing pilot applications, interim remedial measures, or completed pilot projects that are now in the full-scale design phase. The technology has successfully been applied to the following chlorinated compounds:

- Trichloroethene, cis-1,2-dichloroethene, vinyl chloride, carbon tetrachloride, chloroform, chlorinated propanes, pentachlorophenol, pesticides, trichlorofluoromethane, and perchlorate
- Hexavalent chromium, nickel, lead, cadmium, mercury, and uranium.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

As late as 1998, the conventional remediation option for sites contaminated with CAHs was pump-and-treat technology, where impacted groundwater is removed to the surface for treatment and discharge. Pump and treat has well-known limitations associated with long-term operation 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 decreasing portions of contaminant mass with time. Established remediation methods for metals removal also employ groundwater extraction followed by ex situ treatment. Like pump and treat for CAHs, these remedial techniques are costly and require long periods of time to complete.

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

- ERD 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.
- It promotes reduction of residual contaminant mass through desorption and disruption of the contaminant phase equilibrium.
- It is 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.
- It can be used in tandem with existing remediation systems to optimize performance.
- It 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 reagent delivery and remediation efficacy. Mass transfer and distribution rates in porous media are the primary factors influencing the efficiency of the ERD technology. 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. Other potential limitations to the application of the ERD technology 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 carbohydrate solution 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 reactive zone.
- Systems with large amounts or influxes of electron acceptors such as oxygen, nitrate or soluble iron can require large doses of substrate.
- Potential production of excessive quantities of reduced gases such as methane can be problematic in the vicinity of confined structures.
- Molasses in its pure form contains concentrations of several metals. In a dilute mixture, as is typically used in ERD applications, the concentrations have been below regulatory standards, but 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 to harmless end products.
- 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 ERD does appear to be applicable to sorbed or residual DNAPL (Lutes et al, 2004).
- Aldehydes, ketones, and mercaptans can be generated through fermentation but 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 CAHs in the saturated zone include chemical oxidation with permanganate or Fenton’s reagent as well as various forms of reductive iron barriers.

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3.0 SITE/FACILITY DESCRIPTION

3.1 PERFORMANCE OBJECTIVES

The two demonstrations were performed as a series of ESTCP/Air Force Center for Environmental Excellence funded demonstration projects that aim to evaluate the efficacy of the ERD technology to remove CAHs from the impacted groundwater in a range of geologic conditions and CAH concentrations. Primary and secondary performance objectives, as established and discussed in the demonstration plans, are presented in Tables 1 and 2.

3.2 SELECTION OF TEST SITES

The sites chosen for this demonstration were selected and proposed based on ARCADIS' review of obtainable site characterization data. The qualifying criteria used during this initial site review included the following issues:

- Depth (size) of the contaminated aquifer requiring treatment—generally, of little technical significance, but there are cost implications as depth increases
- CAH concentrations, preferably exceeding 10 times the treatment standard or three 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
- At the time this demonstration program started we preferred to conduct it on a site with no DNAPL present; more recently, through other funding, greater evidence of this technology's effectiveness on DNAPL has been developed (Lutes et al, 2004). As discussed later, although the Hanscom demonstration area was initially believed to be downgradient from a source, it was later determined to be a source zone, based on several lines of evidence.
- Available sulfate mass must correspond to the microbiology that is appropriate for the type of ERD desired. At the time of site selection, there was concern that high-sulfate aquifers may not be conducive to developing microbiology that is appropriate for CAH remediation. More recent results suggest that the technology can be applied under high sulfate conditions.

Sites that show some evidence of slow biodegradation are desirable, including those "stalled" at cis-DCE and VC. Existing redox conditions that are anaerobic or borderline aerobic/anaerobic but with insufficient TOC can be most rapidly treated. Anaerobic sites with sufficient degradable TOC may not be aided substantially by addition of soluble carbohydrates.

In addition to technical constraints, economic issues were considered; thus, factors such as depth to the water table and proximity to an ARCADIS office were important in demonstration site selection. Lastly, the sites were judged as to whether they were good "field laboratories." For instance, sites with extremely low groundwater velocities were eliminated as incompatible with a short-term field demonstration. Tables 3 and 4 summarize evaluation criteria for implementing IRZ technology at both sites as compared to established site screening parameters.

Table 1. Performance Objectives, Hanscom AFB.

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; Yes, in a limited area, for cis-DCE;
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
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 Specific Conductance 10x increase Monitoring Wells: pH >5.0 DO <1.0 mg/L ORP <-200 mV TOC >50 mg/L Specific Conductance 20 - 50% increase	Generally yes; continuously "tuned" system to metrics, determined required strength, frequency of injections

Table 1. Performance Objectives, Hanscom AFB (continued).

Type of Performance Objective	Secondary Performance Criteria	Expected Performance (Metric)	Actual Performance Objective Met?
Quantitative	9. Hazardous Materials	Potentially hazardous materials limited to soil cuttings from well drilling and purge water	Yes; no other hazardous 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 hazardous waste operations and emergency response (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 2. Performance Objectives, Vandenberg AFB

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) for a protocol on the 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	Not clearly demonstrated due to duration of test; rates were more rapid than NA, but slower than many other applications of ERD
Quantitative	3. Contaminant Reduction (%)—Reduce total CAH concentrations from baseline levels of d) >200 ppb e) 50 to 200 ppb f) <50 ppb	a) 80% in 1 year b) 75% in 1 year c) 50% in 1 year	Objective was not met for total CAHs within target time. Individual compounds were reduced by ≥80% at specific wells by the post-treatment period: 85% TCE reduction at 35-MW-16 and 80% at 35-MW-7
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 for cis-DCE in limited area; VC and ethene levels have not progressed far enough to completely evaluate; however, progression from TCE degradation to DCE degradation and on to VC is occurring
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	Monitoring wells: DO to <1 mg/L; Oxidation reduction potential (ORP) <50 mV; TOC >50 mg/L	Yes; anaerobic environment created within a large 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, but mostly not applicable; primarily a dissolved phase, low-TOC plume
Quantitative	7. Contaminant Reduction (Rate)—Evaluate degradation rates before and after treatment	Calculate k	Yes

Table 2. Performance Objectives, Vandenberg AFB (continued).

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 DO <1.0 mg/L -400 mV <ORP <-250 mV 500 mg/L <TOC <9,000 mg/L Sp. Cond. 10x increase Monitoring Wells: pH >5.0 DO <1.0 mg/L ORP <-200 mV TOC >50 mg/L Specific conductance 20 - 50% increase	Variable, but generally yes; continuously "tuned" system to metrics, determined required strength, frequency of injections; addition of buffer improved control
Quantitative	9. Hazardous Materials	Potentially hazardous materials limited to soil cuttings from well drilling and purge water	Yes; no other hazardous materials generated
Qualitative	10. Reliability	No significant reliability issues anticipated	Yes
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 (though this is true, there were no other constituents of concern (COCs at this site
Qualitative	13. Maintenance	Maintenance limited to occasional well development, normal equipment maintenance by technician	Yes
Qualitative	14. Scale-Up Constraints	Scale-up potential determined	Yes, but not yet done

In summary, upon initial review, both Hanscom AFB and Vandenberg AFB provided fairly standard sites for ERD implementation. In retrospect, several factors complicated both sites, including variable gradient/potentiometric surface and the relative complexity of subsurface lithology at Hanscom and the low buffering capacity and nonhomogeneous flow field at Vandenberg. However, successful demonstrations were conducted. Sites that may not be suitable demonstration sites or “test beds” for a technology may still be effectively treated with a given technology.

3.3 TEST SITE/FACILITY HISTORY/CHARACTERISTICS

Hanscom AFB. Hanscom AFB is located in Middlesex County, Massachusetts. The area of interest for the demonstration of ERD technology at Hanscom was downgradient from Site 1. 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 (Haley and Aldrich, 1998). CAHs have been detected in groundwater in a narrow plume that 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 5). The features of the demonstration zone in the vicinity of RAP1-6 well cluster, including the overrun for Runway 23, a drainage channel, and nearby monitoring wells, are shown on Figure 6.

The area in the immediate vicinity of Site 1 is underlain by 18 to 25 ft of glacial till overburden that rests directly on granitic bedrock. The till comprising the lower aquifer 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. Hydraulic conductivity values for the lower aquifer range between 3 ft/day to 48 ft/day, and average 26 ft/day (CH2M Hill, 1997). The hydraulic gradient of the lower aquifer in the vicinity of RAP1-6T has been estimated at 0.006, and the effective porosity of the lower aquifer materials was estimated at 20% (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.

The depth to groundwater has ranged from 2 to 9 ft below ground surface (bgs) in the demonstration area. 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.

The natural regional groundwater flow direction is to the east/northeast (CH2M Hill, 1997). This is manifested by the plume orientations, which may predominantly reflect historical groundwater flow patterns rather than current ones. Current groundwater flow patterns are complicated by the number of pumping influences at the site, which create more radial flow patterns from the west to the east and from the southwest to the northeast. The predominant groundwater flow in the demonstration area in 1998 was from the northwest to southeast (bending eastward in the vicinity of RAP1-6T).

Table 3. 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/yr – 5 ft/day	<30 ft/yr >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 was not considered appropriate for targeting pooled DNAPL in 1999 when the demonstration program began	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 ft can become expensive	50 ft
CAH concentration	Nontoxic	Toxic	Nontoxic

Table 4. Suitability of Vandenberg AFB Site Screening Characteristics for IRZ Implementation.

Site Characteristic	Suitable for IRZ	Unsuitable for IRZ	Vandenberg AFB
Aquifer hydraulic conductivity	>1 ft/day	<0.01 ft/day	0.9 – 3.8 ft/day
Groundwater velocity	30 ft/yr – 5 ft/day	<30 ft/yr >5 ft/day	0.11 – 0.46 ft/day
pH	6.0 – 8.0	<5.0, >9.0	6-7
Natural attenuation of CAHs	Slow, complete degradation, or stalled degradation	No degradation	Slow
DNAPL presence	None, or emulsified, sorbed, or residuals	IRZ was not considered appropriate for targeting pooled DNAPL in 1999 when the demonstration program began	No DNAPL known to be present
Sulfate	<700 ppm		200-300 ppm
Redox	Aerobic or borderline	Anaerobic with sufficient TOC	Aerobic (DO >1 mg/l) and oxidizing (ORP >300 mV)
Depth of Target Zone		>50 ft can become expensive (as also true with other technologies)	45 ft
CAH concentration	Nontoxic	Toxic	Nontoxic

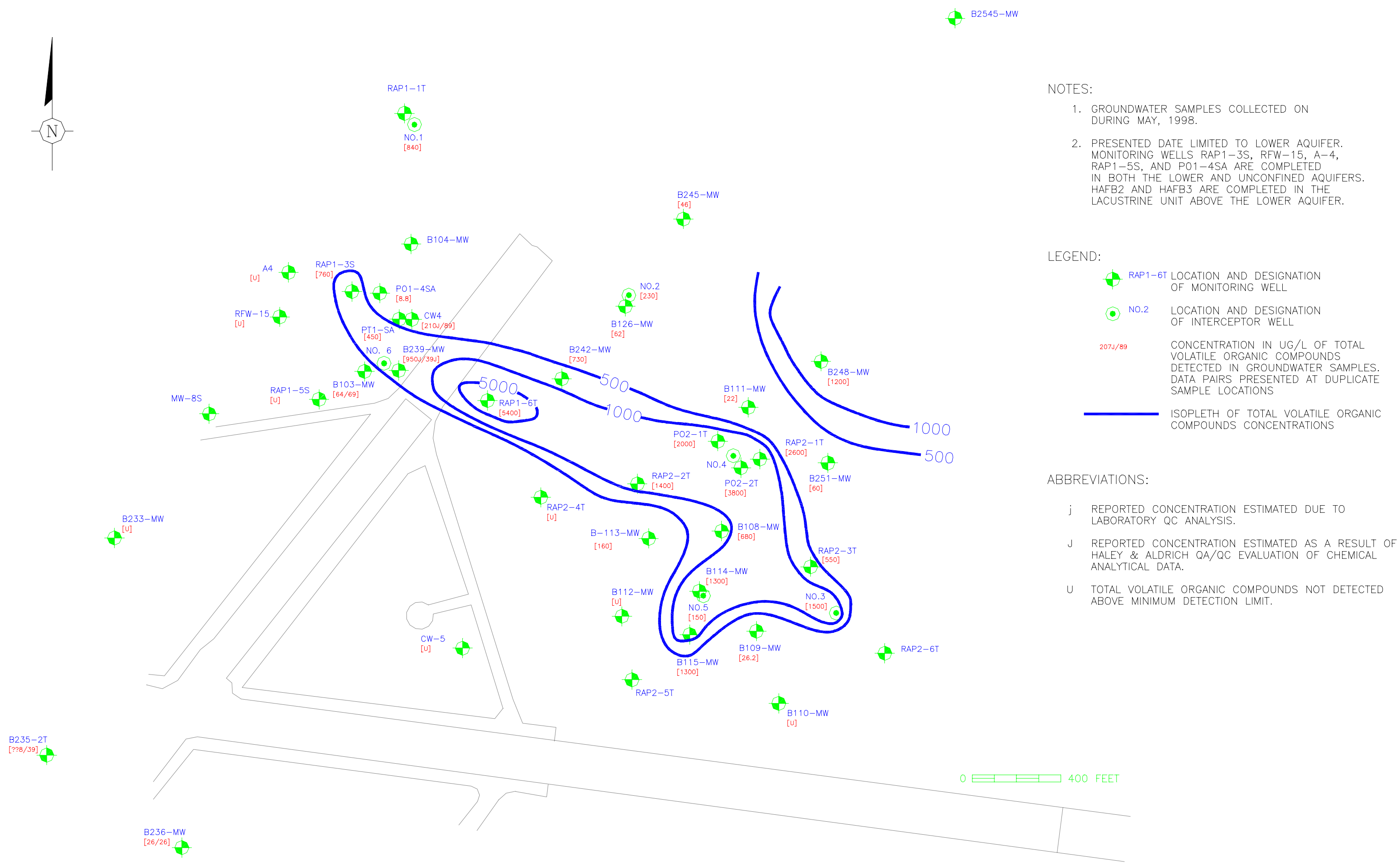

Figure 5. Total Volatile Organic Compound (VOC) Concentrations in Lower Aquifer Near RAP1-6T, May 1998—HAFB

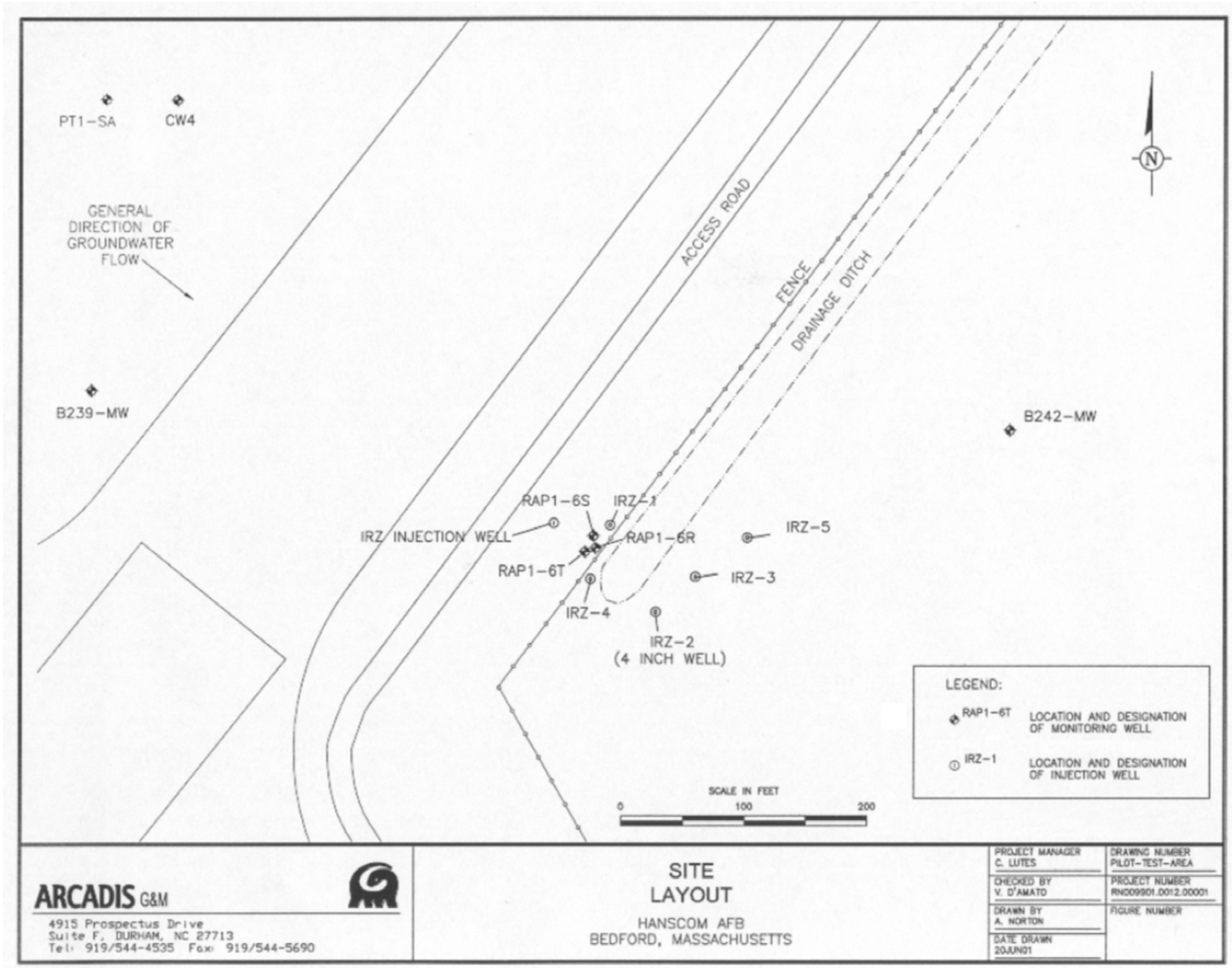

Figure 6. Hanscom AFB Site Layout, Pilot Test Area

Residual CAHs remain beneath Site 1 in the adsorbed and dissolved phases and potentially as residual DNAPL. CAHs have been detected in groundwater in the unconfined, lower, and fractured bedrock aquifers. The predominant CAHs detected in groundwater have been TCE and cis-DCE.

The semiconfined aquifer in the lower till unit was targeted for the pilot demonstration. This aquifer contains elevated total volatile organic compound concentrations ranging up to 5,400 micrograms per liter (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-trichloroethane, as well as biotic degradation compounds such as cis-DCE, 1,1- dichloroethane, and VC. Also present is 1,1-DCE, further suggesting the abiotic transformation of trichloroethane via elimination reactions.

The behavior of chlorinated solvent plumes with respect to reductive dechlorination has been categorized into three types (USEPA, 1998). In this classification system, Hanscom appears to be a Type 1 site. Clear evidence of the first stage of TCE degradation to cis-DCE was observed before treatment. This site may have been "stalled" at cis-DCE, although some VC production was probably also present under pretreatment conditions.

The current remedy at Hanscom Field consists of pump and treat collection trenches and recovery wells, coupled with a vacuum-enhanced recovery (VER) demonstration/pilot in the source zone. The pump and treat system was installed in 1998-1991 and has been operated round the clock since May 6, 1991. Collection trenches have essentially cleaned up the shallow unconfined aquifer, resulting in very limited areas of residual impact around the original source locations.

Vandenberg AFB. The demonstration site at Vandenberg AFB was at Site 35 in the northern pert of the base. Atlas F missile silo facilities such as that at Site 35 reportedly used "dry pad" technology for launches. Dry pad facilities typically generated waste during missile launches, such as TCE, mixed solvents, lubrication oils, and hydraulic fluids (Reynolds, 1985).

The stratigraphy of the site includes Orcutt Formation sediments at the surface, deposited unconformably on Sisquoc Formation shale and mudstone. The Orcutt Formation consists of loosely consolidated lenticular beds of sand, gravel, and clay of predominantly continental origin, with the upper zone representing eolian and beach sand (SAIC, 1990). The thickness of the Orcutt formation is approximately 40 ft in the demonstration area.

Groundwater is unconfined and occurs within the Orcutt formation sands. Beneath the demonstration area at Site 35, the depth to groundwater is approximately 10 to 15 ft bgs, and the depth to bedrock is approximately 40 ft bgs. The predominant direction of groundwater flow is to the southwest, following the topography of the Sisquoc Formation bedrock, with a local hydraulic gradient of approximately 0.041 ft per ft (calculated between Site 35 wells 35-MW-7 and 35-MW-8), and a Site 35 hydraulic gradient of approximately 0.043 ft per ft. A layer of clayey weathered bedrock (Tetra Tech, 1999) reported at the Sisquoc/Orcutt formation contact and the low permeability Sisquoc shale are interpreted to prevent the flow of shallow groundwater into underlying bedrock.

A step drawdown test in August 2000 yielded a hydraulic conductivity (K) estimate of 0.92 to 3.83 ft/day, consistent with a silty sand material characteristic of the Orcutt formation at Site 35. Using this range of K values, average linear groundwater velocity was 0.11 to 0.46 ft/day.

Chlorinated solvent impacts to groundwater at Site 35 consist primarily of TCE, and to a lesser extent degradation daughter products cis-DCE and trans-1,2-DCE (trans-DCE). TCE-impacted groundwater is present at its highest concentrations immediately southwest and downgradient from the Site 35 facilities. The maximum predemonstration concentration was from a Hydropunch™ sample at the bottom of the saturated zone, which had a TCE concentration of 6,200 µg/L. Well 35-MW-7, subsequently installed adjacent to this sample, exhibited 2,900 µg/L TCE in 1998. Based on the predemonstration groundwater data, well 35-MW-7 was at the area of highest TCE groundwater impacts at Site 35.

Metals were reported in Site 35 groundwater samples from 1996-1998, some at concentrations exceeding background threshold values and California drinking water primary maximum contaminant levels (MCL). However, filtered groundwater samples contained far lower concentrations; only nickel was reported in well 35-MW-1 at concentrations exceeding the MCL of 100 milligrams per liter (mg/L).

Microbial counts conducted on Site 35 groundwater samples in September 2000 established the numbers and types of bacteria present before the demonstration. Phospholipid Fatty Acid (PLFA) analysis suggested the existence of an actively dividing, gram negative bacterial community in a nontoxic environment. Denaturing gel electrophoresis (DGGE) analysis showed a bacterial community dominated by facultatively anaerobic gram negative bacteria.

At Vandenberg, predemonstration TOC levels (presumably of natural origin) were limited, ranging from 4 to 6 mg/L. Background DO levels above 1 mg/L indicate an aerobic setting. However, the first stage of TCE degradation to cis-DCE was observed to a very limited extent before treatment. Plume behavior thus had characteristics of both Type 2 (natural carbon source, slow biodegradation) and Type 3 (low carbon, aerobic) behavior. However, in spite of evidence of partial biodegradation, the biochemistry suggested that Type 3 behavior predominated.

3.4 PHYSICAL SETUP AND OPERATION

Physical setup for both systems 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 areas are shown in Figures 6 and 7.

The temporary equipment required for the injections included the following: a solution mixing/holding tank, a gasoline powered transfer pump, and an injection hose. Figure 3 presented a schematic of the Vandenberg injection system (similar to that used at Hanscom).

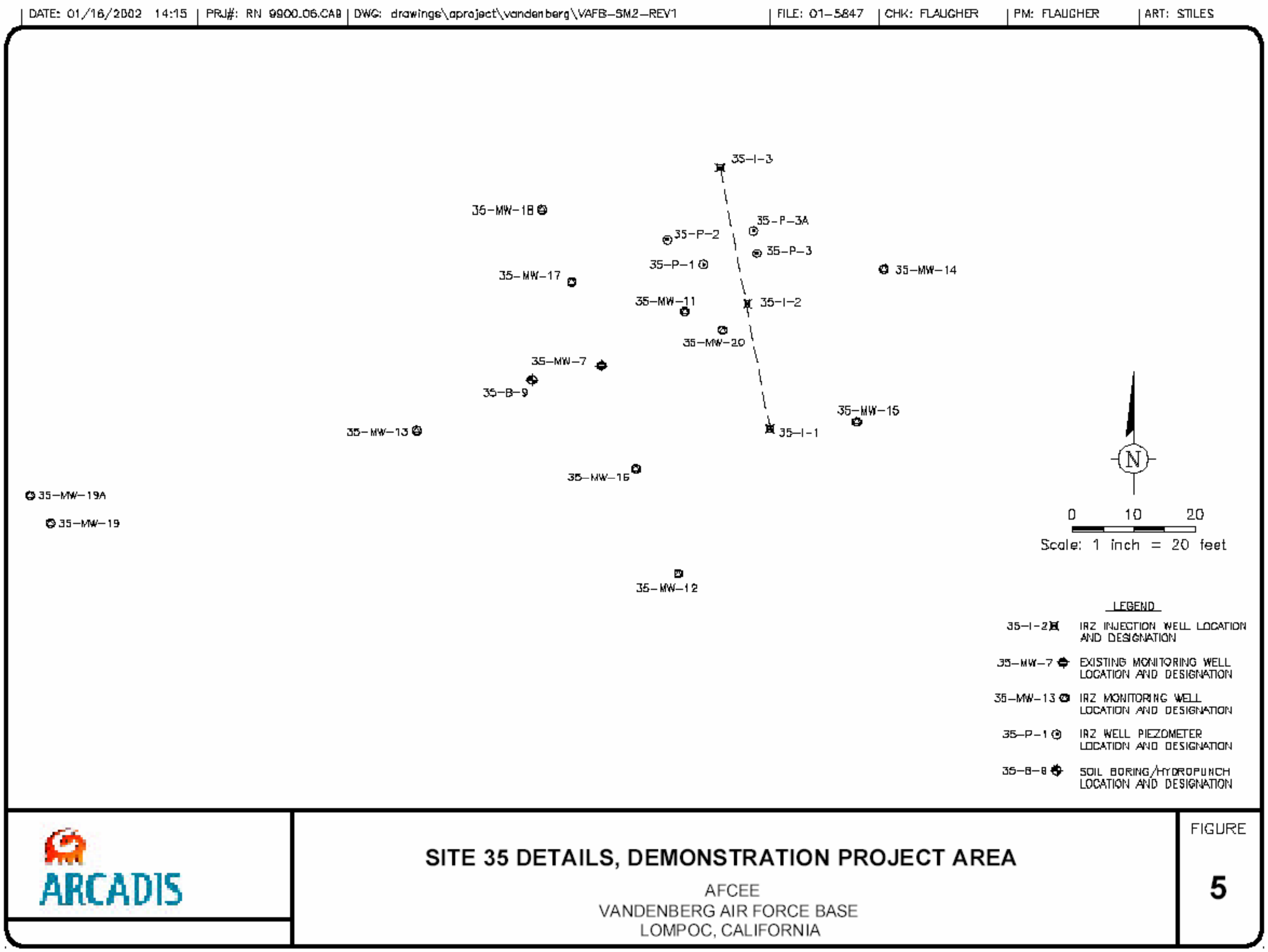

Figure 7. Vandenberg AFB Site Layout, Pilot Test Area.

Start-up testing of the injection system involved filling the tank with water to check for leaks. The tank and associated pumps generally functioned without difficulty. Temporary equipment, molasses, and reagents (bromide tracer), were stored in an on-site building. A pick-up truck was used to transport the equipment to the injection well for each injection event.

Injection events generally involved first testing pH in the injection well and consulting the project manager's guidance as to which injections to make, depending on the observed pH. Then the reagent solution was mixed manually, the injection system was connected to the injection system, and the solution was pumped into the wells. During some events, the solution injection was followed by an injection of clean water. A typical single batch of reagent solution consisted of 20 gal of food-grade blackstrap molasses, 180 gal of potable water, and 113 grams of potassium bromide. The reagent solution was mixed by partially filling the solution tank with water, adding molasses and potassium bromide to the tank, stirring the tank manually for several minutes with a polyvinyl chloride stir rod, and then filling the tank to the desired volume with clean water.

Reagent solution injections proceeded at rates of approximately 1 to 10 gal per minute at observed well head pressures of approximately 2 to 20 lbs per square inch gauge (psig). Labor required for injection events was approximately 4 to 8 hr for a single batch injection, with an additional 1 to 6 hr for a double-volume injection.

Very little maintenance or repair work was required during the demonstration. At Hanscom, indirect evidence of biological growth in and around the injection well was observed as a decrease in the maximum obtainable reagent injection rate and an increase in injection pressure after the first several injection events. This observation was coincident with a small amount of reagent solution leakage into the injection well vault from between the well casing and the surface seal. Corrective action employed by the field staff included lowering the injection pressure by reducing pump speed or in some cases performing the injections under gravity flow. At Vandenberg, one injection well was redeveloped to improve its performance.

At Hanscom, 47 substrate injections were made between October 2000 and October 2002. A total of 1,250 gal of raw blackstrap molasses, 11,250 gal of dilution water, 7,575 gal of push water and 4,732 grams of potassium bromide were injected into one well. At Vandenberg, 31 substrate injections were made between February 2001 and April 2003. A total of 683 gal of raw blackstrap molasses, 6,830 gal of dilution water, 1,500 gal of push water, and 7,718 grams of potassium bromide were injected into the system of three injection wells. 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.

3.5 SAMPLING/MONITORING AND ANALYTICAL PROCEDURES

Experimental designs for the project were established in the demonstration plans (ARCADIS, March 2000; ARCADIS, April 2000). In brief, the types of measurements made are listed below.

- *Soil characterization*. Soil samples were collected during well installation and analyzed for VOCs, TOC, and grain size distribution.
- *Process monitoring*. In 13 periodic events at Hanscom and 29 events at Vandenberg, DO, pH, ORP, specific conductance, temperature, and water level were measured as indicators of biogeochemical changes. In addition, field test kits were used to analyze for hydrogen sulfide and ferrous iron, and laboratory analysis was conducted for bromide and TOC.
- *Full and abbreviated performance monitoring*. At Hanscom, three full and five abbreviated performance monitoring sampling rounds were conducted. At Vandenberg, three full and four abbreviated rounds were conducted. For both demonstration sites, samples were analyzed for VOCs, including TCE, cis-DCE and VC; metals, redox indicators; dissolved gases; volatile fatty acids; general water quality parameters; and microbial tests (Tables 5 and 6).
- *Process control*. Carbon dosing and water pushes were varied in injection events based on continuous evaluation of groundwater monitoring data.

At Hanscom (Figure 6), the injection well was identified as such; monitoring wells were B-239, the RAP1-6 well cluster, and IRZ-1 through 5. At Vandenberg (Figure 7), the three injection wells were 35-I-1 through 3; monitoring wells were 35-MW-7, 35-MW-11 through 18, 35-MW-19A and 35-MW-20.

Full groundwater monitoring events were conducted with a full contingent of quality assurance/quality control (QA/QC) samples. Abbreviated monitoring events, conducted with a lower level of QA/QC, provided additional time points to help analyze changes in the characteristics and extent of the IRZ. Abbreviated events also provided valuable feedback data on biogeochemical conditions, to assist in making decisions on the amount of substrate to inject, thus controlling the reactive zone. Groundwater sampling methods during full and abbreviated performance monitoring rounds utilized low-flow, or micropurge procedures, consistent with Environmental Protection Agency (EPA) and AFCEE published protocols.

Low QA/QC process-monitoring rounds included, at a minimum, pH, DO, specific conductance, and ORP. TOC and/or dissolved organic compound (DOC) were sampled when other indicators suggested the possibility of carbon overloading leading to fermentation. Injection well pH was measured before every injection event. At Hanscom, additional samples were obtained at intermediate time points for analysis by the Base’s field gas chromatograph (GC) to obtain additional information about TCE and cis-DCE.

Process monitoring events were more frequent near the beginning of the injection programs, 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.

Table 5. Groundwater Analytical Parameters.

Parameter	Analytical Method	Reporting Units	Volume, Container, Preservative and Storage Requirements	Hold Time	Parameter Also Included in Abbreviated Monitoring Events?	Location of Test/Firm
Temperature	ARCADIS standard operating procedure (SOP) D1 (based on EPA 170.1)	°C	NA	Analyze immediately	Y	ARCADIS/field
ORP	See appendix field procedures and instrument calibration procedures	mV	NA	Analyze immediately	Y	ARCADIS/field
Dissolved Oxygen	ARCADIS SOP D5 (based on EPA 360.1)	mg/L	NA	Analyze immediately	Y	ARCADIS/field
pH	ARCADIS SOP D2 (based on EPA 150.1)	Standard Unit (S.U.)	NA	Analyze immediately	Y	ARCADIS/field
Specific Conductance	ARCADIS SOP D3 based on standard methods for examination of water and wastewater, 15th edition method 205 and USEPA method 120.1	Microsiemens/cm	NA	Analyze immediately	Y	ARCADIS/field
Alkalinity	310.1	mg/L	250 mL glass or plastic Cool to 4°C	14 days	N	STL
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	µg/l	Glass volatile organic analysis (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	Severn Trent Laboratories (STL)

Table 5. Groundwater Analytical Parameters (continued).

Parameter	Analytical Method	Reporting Units	Volume, Container, Preservative and Storage Requirements	Hold Time	Parameter Also Included in Abbreviated Monitoring Events?	Location of Test/Firm
Biochemical Oxygen Demand	405.1	mg/L	100 mL glass or plastic Cool to 4°C	48 hours	N	STL
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 TOC	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/field
Total Iron	6010B and CHEMetrics kit in field	µg/L	1 L glass or plastic HNO_3 to pH<2	6 months	N	STL and field/ ARCADIS
Total Manganese	6010B and CHEMetrics kit in field based on APHA 314C	µg/L	1 L glass or plastic HNO_3 to pH<2	6 months	N	STL and field/ ARCADIS
Dissolved Iron	6010B and CHEMetrics kit in field	µg/L	1 L glass or plastic HNO_3 to pH<2	6 months	N	STL and field/ ARCADIS
Dissolved Manganese	6010B and CHEMetrics kit in field (APHA 314C)	µg/L	1 L glass or plastic HNO_3 to pH<2	6 months	N	STL and field/ ARCADIS
CAHs	8260	µg/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
Bromide	300.0	mg/l	250 ml plastic or glass unpreserved	28 days	Y	STL

Table 6. Soil Analytical Parameters

Parameter	Analytical Method	Reporting Units	Container & Preservative Requirements	Hold Time	Parameter Included also In Abbreviated Monitoring Events?	Location of Test
TOC	9060	mg/kg	None specified	28 days	Y	STL
CAHs	8260	µg/kg	4 oz glass with Teflon lined septa; store at 4°C	14 days	Y	STL
Grain Size	ASTM D-422	% passing	500 mL wide mouth glass or plastic (purchased by field crew)	None	Y	ECS

3.6 ANALYTICAL PROCEDURES

Analytical parameters, methods and laboratories are specified in Tables 5 and 6. Records were kept of the color, odor and other readily apparent characteristics of the sampled groundwater. Further details of these methods are contained in the demonstration plans. Additionally, some groundwater samples at Hanscom were analyzed on-site by the Base's GC (operated by an independent contractor; see Appendix A-3 of the Final Technical Report).

Process monitoring was conducted using portable field instrumentation and varied from down-well sondes to flow-through cells to measure DO, pH, ORP, specific conductance, and temperature. Field instruments used in the program were identified in SOPs contained in the project demonstration plans (ARCADIS, March 2000; ARCADIS, April 2000). Field test kits were used to analyze for hydrogen sulfide and ferrous iron.

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4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE DATA

Summary results for the demonstrations are given in Tables 7 and 8. More detailed data summaries are given in the Final Technical Reports for the demonstrations (ARCADIS, April 2004 and December 2004).

The demonstration-scale system at Hanscom AFB was operated between October 2000 and October 2002. During that time, highly effective, complete TCE removal was demonstrated 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-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, but 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.

During the 26-month period of active treatment at Vandenberg, and for as long as 3 months after the last injection, the treatment system demonstrated slow but effective TCE removal by biodegradation in a dissolved phase plume that showed very limited TCE degradation before treatment. Multiple lines of evidence of complete treatment—production of ethene, reduction in cis-DCE and no accumulation of VC—were seen in the most effectively treated downgradient wells. Effective treatment was seen only where substantial substrate and anaerobic conditions were observed in downgradient monitoring wells. The rate of treatment was significantly affected by the low buffering capacity of the aquifer, which initially limited the carbon dosing rate, thereby slowing the performance of the treatment system. Addition of a buffer to the injectate starting in October 2002 allowed a substantial increase in the dosing rate and resulted in improved CAH biodegradation. Treatment was also somewhat uneven within the targeted zone due to nonhomogeneous groundwater flow patterns; however, a substantial zone was established with a limited number of injection wells.

4.2 PERFORMANCE CRITERIA

Performance criteria, confirmation methods and brief summaries of results are listed in Tables 9, 10, and 11. Because of the complexity of the demonstrations (including the nature of the geological settings and the biology of CAH biodegradation), results are not easily presented in the standard tabular format for these reports. Therefore, references to relevant text in the Final Technical Reports are included as needed. The most important performance assessment methods used in the demonstrations are described briefly below.

<u>Groundwater Flow Field Evaluations</u>

Water-level data collected during groundwater sampling events (prior to injections) were mapped to monitor the direction of groundwater flow during the demonstration area. Mounding effects at the injection wells were generally small, and evidence of preferential flow paths was often noted.

Table 7. Performance Data, Hanscom AFB.

In Situ Reactive Zone Technology for Treatment of Chlorinated Aliphatic Hydrocarbons, Hanscom AFB	
Types of samples collected	Groundwater analyzed for VOCs, including TCE, cis-DCE and VC; metals, redox indicators; dissolved gases; volatile fatty acids; general water quality parameters; and microbial tests. Soil analyzed for VOCs, TOC, and grain size analysis.
Sample frequency and protocol	Groundwater sampled in three full rounds (baseline, midpoint, final); five abbreviated rounds for VOCs and fewer supplementary analyses (interspersed with full rounds); and 13 process monitoring events for field parameters, TOC, and bromide only (generally preceding injection events). Additional, informal data is available from on-site GC analysis for TCE and DCE. Soil analyzed at baseline only.
Quantity of material treated	Size of demonstration-scale reactive zone estimated at <100 ft long by 40 ft wide by 18-25 ft thick
Untreated and treated contaminant concentrations	Baseline VOC concentrations at two wells were 810-1,100 µg/L TCE, 2,100-3,500 µg/L cis-DCE, 660-1,100 µg/L VC. At end of active treatment, same wells ranged from 68-510 µg/L TCE, 980-3,300 cis-DCE, 650-1,000 µg/L VC. Post-active treatment (7-17 months after last injection), same wells contained <10 µg/L TCE, <14-9 µg /L cis-DCE, 6-34 µg /L VC.
Cleanup/demonstration objectives	Total CAH concentrations reduced by at least 80% in 1 year
Comparison with cleanup objectives	Reductions in TCE concentrations exceeded 80% within 6 months at wells with best substrate delivery. Daughter products required more than one year to reach target: 17 to 26 months for cis-DCE (compared to 24 months of active treatment), 31 months for VC (7 months after end of active treatment). In the post-active treatment period, concentrations continued to decrease.
Method of analysis	Used standard EPA and SW-846 lab methods for most analyses. Field parameters measured on site with down-hole meters or in flow-through cells. Some inorganics analyzed on site with field test kits. Dissolved gases, volatile fatty acids, microbiological and soil grain size analyses performed at specialized labs. Some supplementary VOC samples were analyzed on site using a GC.
QA/QC	Quality Assurance Project Plan (QAPP) prepared for project. Relatively few data quality problems were identified, and most of these were judged inconsequential or were resolved by resampling or relying on alternate measurements of the same parameter. High carbon levels at injection wells caused difficulties with field parameter measurements.
Other residues	Purge water was treated in a wastewater treatment process and disposed of. Soil cuttings from well drilling were stored in 55-gal drums, characterized and disposed of at a licensed hazardous materials disposal facility.

Table 8. Performance Data, Vandenberg AFB.

In Situ Reactive Zone Technology for Treatment of Chlorinated Aliphatic Hydrocarbons, Vandenberg AFB	
Types of samples collected	Groundwater analyzed for VOCs, including TCE, cis-DCE and VC; metals; redox indicators; dissolved gases; volatile fatty acids; general water quality parameters; and microbial tests. Soil analyzed for VOCs, TOC, and grain size analysis.
Sample frequency and protocol	Groundwater sampled in three full rounds (baseline, midpoint, final), four abbreviated rounds for VOCs and fewer supplementary analyses (interspersed with full rounds), and 29 process monitoring events for field parameters, TOC, and bromide only (generally preceding injection events). Additional, limited groundwater monitoring data available from site contractor and an EPA-Ada field study. Soil analyzed at baseline only.
Quantity of material treated	Size of demonstration-scale reactive zone estimated at 20 to 125 ft long by 16 ft wide by 10 ft thick
Untreated and treated contaminant concentrations	Baseline VOC concentrations at four wells were 410-1,600 µg /L TCE, 9-31 µg/L cis-DCE, ND–10 µg/L VC. At end of active treatment, same wells ranged from 130-410 µg/L TCE, 59-450 cis-DCE, 0.3-26 µg/L VC. Post-treatment, TCE same wells ranged from 208-257 µg/L TCE, 50-559 cis-DCE, 15-169 µg/L VC.
Cleanup/demonstration objectives	Total CAH concentrations reduced by at least 80% in 1 year
Comparison with cleanup objectives	Objective was not met for total CAHs within target time, but individual TCE reductions were ≥80% at specific wells in the post-treatment period. Total molar CAH reductions ranged from 12-66%. Due to an early buffering problem and long lag times for TCE degradation, cis-DCE and VC concentrations had not yet peaked at most reactive zone wells by the end of the post-demonstration monitoring period. More rapid, complete treatment would require more intensive substrate delivery.
Method of analysis	Used standard EPA and SW-846 lab methods for most analyses. Field parameters measured on site with down-hole meters or in flow-through cells. Some inorganics analyzed on site with field test kits. Dissolved gases, volatile fatty acids, microbiological and soil grain size analyses performed at specialized labs.
QA/QC	QAPP prepared for project. Relatively few data quality problems were identified, and most of these were judged inconsequential or were resolved by resampling or relying on alternate measurements of the same parameter.
Other residues	Purge water was treated in a wastewater treatment process and disposed of. Soil cuttings from well drilling were stored in 55-gal drums, characterized and disposed of at a licensed hazardous materials disposal facility.

Table 9. Performance Criteria.

Performance Criteria	Description	Primary or Secondary
Technology evaluation	Gather information for a protocol using IRZ technology for CAHs at Department of Defense (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; primarily TCE and cis-1,2-DCE at Vandenberg 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 levels, 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 operation and maintenance (O&M)	Secondary
Scale-up constraints	Identify engineering constraints associated with scaling up an ERD system	Secondary

Table 10. Performance Summary, Hanscom AFB.

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	Cis-DCE and VC concentrations ultimately reduced by 97 to >99%. 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. Post-treatment, TCE and cis-DCE reduced >99% , VC 97% (7-17 months after last injection) RAP1-6T: TCE reduced >80% in 1 year, >99% in 24 months. Post-treatment, cis-DCE and VC reduced 99% (13-17 months after last injection)
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 Specific conductance. 10x increase Monitoring Wells: pH >5.0 DO <1.0 mg/L ORP <-200 mV TOC >50 mg/L Specific conductance 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*

Table 10. Performance Summary, Hanscom AFB (continued)

Performance Criteria	Expected Performance Metric (Pre-Demonstration)	Performance Confirmation Method	Actual (Post-Demonstration)
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*
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 Sections 5.7 and 6.3 of 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

* Section numbers refer to Final Technical Report for Hanscom AFB (ARCADIS, April, 2004)

Table 11. Performance Summary, Vandenberg AFB.

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 in the reactive zone	Cis-DCE peaked and fell at some reactive zone wells; VC production began recently. Evidence of continuing ethene production
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 may be attainable, though a quantitative determination was not possible
Contaminant reduction (%)	Total CAH concentrations reduced by at least 80% in 1 year	CAH data from 35-MW-16, 35-MW-7, 35-MW-20 and 35-MW-11, from baseline sampling through present	Total molar CAH reductions ranged from 12-66%, TCE reductions were 42-74% at end of active treatment (see Table 4-17a*). Individual TCE reductions were ≥80% at specific wells in post-treatment period. Cis-DCE and VC generally increased indicating incomplete treatment. More rapid, complete treatment would require more intensive substrate delivery (see Section 4.3.7.1*)
SECONDARY CRITERIA (Performance Objectives) (Qualitative)			
System performance optimization	Injection Wells: pH >4.0 DO <1.0 mg/L -400 mV <ORP <-250 mV 500 mg/L <TOC <9000 mg/L Specific Conductance 10x increase Monitoring Wells: pH >5.0 DO <1.0 mg/L ORP <-200 mV TOC >50 mg/L Specific Conductance 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; low buffering capacity of aquifer caused variability in performance criteria that was mitigated following the addition of a buffer (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 equipment maintenance and optimization of injection well performance (Section 3.5.1*)

Table 11. Performance Summary, Vandenberg AFB*(continued).

Performance Criteria	Expected Performance Metric (Pre-Demonstration)	Performance Confirmation Method	Actual (Post-Demonstration)
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*
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	Monitoring well: DO to <1 mg/L ORP <200 mV	Performance monitoring data evaluated before each injection event	A sufficient anaerobic environment was created within the reactive zone, though substrate delivery was heterogeneous and thus the shape of the downgradient reactive zone was irregular (see Section 4.3.7.2*)
Geochemistry manipulation	Monitoring well: TOC >50 mg/l	Performance monitoring data evaluated before each injection event	Sustained TOC >50 was observed at 35-MW-20 and 35-MW-16. Such TOC levels were briefly observed but not sustained at 35-MW-11 and 35-MW-7.
Contaminant mobility	Presence of "spike" in concentration after initial injections	CAH data for wells 35-MW-7, 35-MW-11, 35-MW-16 and 35-MW-20	In some wells, modest spikes observed in TCE concentrations after active treatment began (see Section 4.3.7.2*)
Contaminant reduction (rate)	Calculate k	k determined from long-term pre-demonstration data at 35-MW-7 and from data trends at 35-MW-7, 35-MW-11, 35-MW-16, and 35-MW-20	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, and purge water	Purge water treated in a licensed treatment system, cuttings from soil borings characterized and disposed of off site

* Section numbers refer to Final Technical Report for Vandenberg AFB (ARCADIS, December, 2004)

Injection Rates and Field Parameter Observations

Reagent injection data were recorded and plotted to demonstrate significant temporal changes in dosing. The effects of the injections were noted at the monitoring wells in terms of standard field parameters (pH, specific conductance, ORP, DO), bromide and TOC data, and visual and olfactory evidence of the presence of molasses and its by-products.

Measures of Reactive Zone Influence

Several measures were used as indicators of reagent delivery and the consequent creation of the reactive zone: the arrival of geochemical changes in such parameters as DO, ORP, TOC and the tracer bromide; the development of redox zones; and visual and visual/olfactory changes in the groundwater. The progression of reactive zones throughout the treatment period was tracked as a series of plots showing zones in which various electron acceptor processes were predominant and in which TOC/bromide levels were elevated and reducing conditions were observed. We caution that DO and ORP measurements are subject to numerous potential interferences, which have led us to deemphasize their use in our recent practice.

Bromide Tracer Data

Bromide tracer data were used to estimate groundwater flow velocity and to calculate the amount of dilution reflected in constituent concentrations measured at monitoring wells.

Biodegradation (Contaminant Reduction) Rates

In order to quantify the rate of decrease of COCs during the demonstration, first-order attenuation rates were calculated for TCE and cis-DCE using exponential regression methods. Rates were compared to those for other chlorinated ethene sites for which data were available and to published biodegradation rate data.

Secondary Water Quality Effects and Gas Production

Constituents that could potentially cause secondary impacts to groundwater quality as a result of the ERD process were monitored during the demonstrations and in the post-treatment period. These included metals in the molasses, breakdown products of molasses, metabolic by-product VOCs (volatile fatty acids, ketones, and carbon disulfide), and other parameters that are affected by the altered geochemistry, such as biochemical oxygen demand (BOD), COD, sulfide, TDS, and metals that can be mobilized from aquifer solids under reducing conditions (especially iron, manganese, and arsenic). The production of hydrogen sulfide and methane gases were also monitored.

Hydrogen Data

Dissolved hydrogen was measured to judge its potential as a diagnostic parameter indicative of predominant redox processes. Sampling confirmed that the cost of acquiring reliable hydrogen data was generally not justified at routine sites since the predominant redox processes can normally be delineated from other chemical measurements.

Microbial Population Characterization

Evaluation of the microbial populations included various testing for PLFA, DGGE, Dehalococcoides ethenogenes, and volatile fatty acids. At Hanscom, since there was strong evidence of natural attenuation before the demonstration, no pretreatment testing was performed. However, microbial characterization was performed during the “final” sampling round in

October 2002. At Vandenberg, testing took place before, during, and after treatment. This characterization is rarely needed in routine commercial implementations of this technology.

4.3 DATA ASSESSMENT

Data collection methods and data analysis procedures used in this demonstration, including the QAPP, were established in the project demonstration plans. The performance of the technology as compared to claims for selected areas of assessment is discussed below.

<u>Contaminant Reduction and Regulatory Standards Attained—Hanscom</u>
The best treatment results were observed at the two monitoring wells that received substantial doses of TOC: IRZ-1 and RAP1-6T, in the reactive zone. At IRZ-1, highly effective treatment of TCE was observed 5 months after injections began (>95% reduction versus pretest concentrations, which greatly exceeds the objective of 80% reduction within 1 year). Well RAP1-6T exhibited a sharp initial decline in TCE, exceeding the 80% objective within 6 months. TCE rebounded temporarily as the IRZ shifted away from the well but later returned to below target levels.

In the post-active treatment period, the 80% goal was attained for the remaining daughter products: at IRZ-1, the expected reductions were seen in cis-DCE within 17 months after the first injection (85%), and in VC by 31 months after the first injection (97%). At RAP1-6T, the expected reductions were seen in cis-DCE in 26 months after the first injection (98%), and in VC by 31 months after the first injection (88%). Additional reductions were seen in subsequent sampling rounds. By 17 months after the end of active treatment, the baseline concentrations of TCE, cis-DCE, and VC had been reduced at the most highly treated wells by 97 to >99%.

The Hanscom demonstration was successful in achieving MCLs for TCE and cis-DCE. Although the concentration of VC has dramatically decreased, the MCL for VC was not attained due to variable groundwater flow directions and thus inconsistent dispersal of reagent. However, generation of ethene indicated that TCE was being completely degraded without “dead-ending” at intermediate compounds. VC would be expected to further degrade downgradient and within the reactive zone over longer treatment periods. The original plans and goals for this project as documented in the demonstration plans never contemplated active treatment all the way to MCLs. It was always anticipated that at these sites, as at most sites that are practically remediated, that a risk-based closure approach would be used. Risk-based closure approaches typically rely on achievement of substantial mass removal/concentration reduction with active treatment plus natural attenuation that occurs downgradient between the active treatment zone and risk receptors. Natural attenuation is also anticipated to contribute to the long term restoration of the active treatment zone after active system operation ceases.

<u>Contaminant Reduction and Regulatory Standards Attained—Vandenberg</u>
The 80% target contaminant reduction for total CAHs was not met within the target time of 1 year, though TCE reductions of ≥80% were reached at specific wells after 26 months of active injections and 3 to 10 months of additional observations. Results in terms of total CAHs and TCE reductions were as follows:

- TCE concentrations for the for the four most highly treated reactive zone wells (35-MW-7, 35-MW-11, 35-MW-16, and 35-MW-20) fell by 42 to 74% during active treatment.
- TCE reductions of 85% were achieved within the post-treatment period at 35-MW-16 (29 months after the first injection; 3 months after the last injection), and 80% TCE reduction was achieved at 35-MW-7, also within the post-treatment period (36 months after the first injection and 10 months after the last injection based on an average pre-treatment concentration of 997.5 μg/L calculated from September through December 2000).
- Multiple lines of evidence of complete treatment—production of ethene, reduction in cis-DCE and no accumulation of VC—were seen in the most effectively treated downgradient wells.
- Total molar concentrations for the four most highly treated reactive zone wells (35-MW-7, 35-MW-11, 35-MW-16 and 35-MW-20) fell by 12 to 66% during active treatment. This range includes desorption peaks and continued production of daughter products late in the treatment period. Because the total molar concentration stays steady until desorption and degradation is complete, it is normal that this metric stays relatively constant or even increases until the last stages of an ERD treatment (Suthersan and Payne, 2005, Section 2.3.1.7.)
- Given the scope and limitation of the demonstration, treatment to current MCLs was neither targeted nor demonstrated, although substantial degradation was.

These reductions include possible natural attenuation effects as suggested by a loss of molar concentration in most monitoring wells during the treatment period. CAHs also decreased in background and cross-gradient wells during the demonstration, apparently due to changes in groundwater flow direction. For example, the concentration at upgradient well MW-15 decreased from 1500 to 1060 μg/L between the initial and post-treatment observations. This well had no significant change in the ratio of TCE to DCE, which suggests that this decrease is due to natural variation, since the ratio changed quite significantly in the more treated downgradient wells. Trends in other up- and side-gradient wells are difficult to generalize so the interested reader should refer to Section 4.3.4 of the Vandenberg final report (ARCADIS, 2004).

Sampling and Data Performance

Sampling generally proceeded according to the expectations of the demonstration plans with regard to frequency and rate. Representativeness, completeness, comparability, accuracy and precision of the demonstration data are addressed in the data validation memoranda in appendices of each Final Technical Report. Relatively few data quality problems were identified, and most of these were judged inconsequential or were resolved by resampling or relying on alternate measurements of the same parameter.

Personnel/Training Requirements

Field implementation of the ERD systems was relatively straightforward as expected, requiring an environmental technician with appropriate safety training, and office support from degreed scientists and engineers. System design and operation oversight were conducted by scientists and engineers experienced in ERD technology. A geologist was required for well installations.

Health and Safety Requirements

Safety issues at both sites 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 solutions or generated during operation of the systems, with the exception of purge water from the wells and gases such as methane and hydrogen sulfide. These conditions met with the expectations of the demonstration work plans, and management of these gases is covered extensively in the protocol document.

Ease of Operation

ERD technology is relatively easy to implement, especially when manual injection methods are used, as at both the Hanscom and Vandenberg sites. Beyond the design and installation phases, field implementation and sampling were done by environmental technicians with office support from managers who were degreed scientists and engineers. These conditions met with the expectations of the demonstration work plans.

Limitations

General limitations of the technology are detailed in Section 2.4 of this report. The site applications discussed here exhibited some unforeseen biogeochemical and hydrogeological characteristics that affected the outcomes of the demonstrations. These are discussed in detail in the Final Technical Reports. In brief, the Hanscom site exhibited some of the difficulties associated with heterogeneous lithology and variable groundwater flow direction (due to variable pumping by a network of unrelated extraction wells), both of which limited our ability to deliver a consistent dose of electron donor to the target area, spatially and temporally. At both sites, the low buffering capacity of the aquifer materials necessitated reductions in carbon doses and other measures (e.g., use of a buffer, water injections) to keep pH within the desired effective range. Inconsistent or non-optimal delivery also prolonged the optimization time required for complete CAH degradation, leading to longer lag times than would otherwise be expected, particularly at Vandenberg.

As expected during an anaerobic biological process, both the Hanscom and Vandenberg demonstrations exhibited secondary water quality impacts within the treatment zone, including formation of metabolic by-products of molasses degradation, mobilization of metals, and increases in BOD/COD. However, as expected, these were limited to the area of the reactive zones and did not appear to be significant downgradient. Almost all of these products are degraded or readsorbed under aerobic conditions encountered at the downgradient edge of the plume. Where there are no immediate potential receptors, as at the two demonstration sites, these impacts do not pose an appreciable risk.

4.4 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 ease of deployment (such as very limited "hard" design); limited permitting and approvals; ease of operations and maintenance; flexibility; limited health and safety risks; and the potential for implementation with little impact to ongoing facility operations 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 demonstrations illustrate some limitations of ERD application in comparison to other technologies. These limitations include the speed at which desired reactions/treatment results can be expected to occur; possible incomplete treatment of parent CAHs; and possible solubilization of inorganics under reducing conditions. There is also a potential for pH shifts to more acidic conditions within the reactive zone during implementation of this technology. In some of the sites in which this technology was demonstrated, the radius of influence observed was limited and requires a high density of injection wells or higher volume injections during full-scale implementation. The technology relies on advective flow for reagent distribution and the acclimation of natural in situ microbial populations, both of which require operational time. The O&M costs during that period must be taken into account in planning. Many of these limitations apply to only a subset of sites or can be overcome with design and operational practices. However, they need to be carefully considered during both the technology selection and remedial design phases of the project.

Table 12 contains a general comparison of ERD to several other common remediation technologies used for the treatment of CAHs. This general comparison considers the relative effectiveness, reliability, speed, and ease of use of each technique for comparison purposes. A comparison specific to conditions at the site can also be made. This comparison is especially valid at the Hanscom site, given that the Base has undertaken numerous remediation projects, including groundwater extraction and treatment, vacuum-enhanced recovery, and in situ chemical oxidation. A discussion of these technologies as they relate to actual or potential applications at Hanscom AFB is outlined below.

<u>Groundwater Extraction and Treatment (Pump and Treat)</u>

Groundwater extraction and treatment has been used 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, due to the presence of source material, the fact that portions of the site are underlain by low permeability geologic materials, and the expansive size of the CAH plumes at the Base, complete 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 (MNA).

<u>Aquifer Sparging</u>

Sparging is often an effective means for remediating CAH impacts. However, at Hanscom this technology is technically unfeasible for the semiconfined aquifer since the confining unit would prevent recovery of the vapors, resulting in the uncontrolled migration of gas-phase CAHs.

<u>Chemical Oxidation</u>

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.

Table 12. Comparison of Technology Alternatives.

Groundwater Pump & Treat	Aquifer Sparging
Effectiveness	
Rapid initial results (containment and mass removal) once system is deployed.	Rapid results (containment and mass removal) once system is deployed.
Effective at dissolved phase concentration; can have a limited effect on mass removal when most of the mass is in sorbed or free phase.	Effective at mass removal of contaminants.
Very effective for hydraulic containment and easily demonstrated.	Effectiveness for containment and plume treatment is more complex to demonstrate in short-term.
Not effective in meeting all but the least stringent cleanup goals.	In situ treatment provides more effective treatment of organics such as VOCs. However, overall effectiveness limited to compounds with high Henry's Law constant or those that can degrade aerobically.
	Limited to particular geologies.
Reliability	
Moderate reliability—number of fixed/engineered components increases likelihood of operational problems/failures.	In situ nature and limited fixed components make technology very reliable.
Fixed, engineered nature of systems severely limits flexibility and adaptability.	Fixed, engineered nature of systems severely limits flexibility and adaptability.
Operational experience suggests systems can be plagued by reliability problems associated with nontarget contaminants (i.e., 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 reliably treated (see above).
Speed	
Short-term - slow speed. Fairly complex design, approval, and permitting process needed for implementation.	Short-term - moderate speed. Reasonable design and 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 requirements, manpower requirements, and residuals management.	Technology is moderately complex due to energy requirements, manpower requirements. Limited residuals management.
Health and safety concerns are moderate. Technology can cause additional routes of exposure to media.	Health and safety concerns are moderate. Technology provides additional routes of exposure to media if gas generation is not well managed.
Above-grade nature of treatment system can impact site activities or development potential.	Above-grade nature of treatment system can impact site activities or development potential.
Effectiveness	
Very rapid results (mass removal) upon application of technology.	Technology will provide effective mass removal upon acclimatization of reactive zone.
Effective at mass removal of certain contaminants.	Effective at mass removal of contaminants.
Effectiveness simple to demonstrate in short-term. Long-term monitoring required to evaluate rebound.	Effectiveness for containment or plume treatment is more complex to demonstrate in short-term.
In situ treatment provides more effective treatment of organics such as VOCs. However, overall effectiveness limited to organic compounds. In addition, mixed organic plumes may require multiple oxidants.	In situ treatment provides more effective treatment of organics such as VOCs. Technology can also be used to treat other compounds, including metals.

Table 12. Comparison of Technology Alternatives (continued)**.**

Chemical Oxidation	Enhanced Reductive Dechlorination
Reliability	
In situ nature and no fixed components make technology very reliable.	In situ nature and no fixed components make technology very reliable.
Lack of fixed, engineered systems make technology flexible and adaptable.	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 reliably treated (see above). Reliability in situ is strongly limited by the need to use high doses to overcome oxidant demand of nontarget compounds.	Larger suite of compounds that can be reliably treated (see above).
Speed	
Short-term—fast speed. Limited design, approval, and permitting process needed for implementation.	Short-term—fast speed. Limited design, approval, and permitting process needed for implementation.
Long-term—ast speed. Nature of technology provides 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	
Technology is moderately complex due to handling of chemicals and the potential for aquifer preparation prior to treatment. However, no residuals management is required.	System design and operation require input from an experienced expert.
Health and safety concerns are high. Technology can create high temperature reactions and high levels of oxygen in the subsurface that need to be addressed.	Technology is very simple to implement. Limited manpower requirements, no residuals management, and no chemical handling concerns.
Below-grade nature of technology and lack of fixed systems limit impacts to site activities and development potential.	Health and safety concerns are primarily attributable to gas generation and can be managed relatively easily.
	Below-grade nature of technology and lack of fixed systems limits impacts to site activities and development potential.

Currently, the Air Force is evaluating this technology at Hanscom using permanganate as the oxidant. At the time of the site report, performance data from these tests was unavailable. Assuming that a chemical oxidant could be delivered to the impacted areas, 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 would 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 for treatment of higher concentration areas or areas where rapid cleanup time periods outweigh cost concerns. Chemical oxidation also has substantial safety concerns.

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 enhanced desorption of adsorbed phase CAHs. Seventeen months after the end of active treatment at Hanscom, concentrations of TCE, cis-DCE, and VC had been reduced at the most highly treated wells by 97 to >99%. No post-treatment rebound was observed. In addition, long-term effectiveness was demonstrated in a source zone.

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.

A variety of methods, including the addition of soluble carbohydrates, used to enhance the anaerobic biodegradation are surveyed in the recent "Principles and Practices of Enhanced Anaerobic Bioremediation of Chlorinated Solvents" (AFCEE, 2004).

5.0 COST ASSESSMENT

5.1 COST REPORTING

5.1.1 Cost Reporting for Hanscom and Vandenberg Demonstrations

As called for in the April 2004 "Cost and Performance Report: Guidance for Cleanup and Site Characterization Projects," we used the Federal Remediation Technologies Roundtable (FRTR) Guide to Documenting and Managing Cost and Performance Information for Remediation Projects (revised October 1998) as a guide to the cost reporting approach. We used the FRTR Revised Cost Format (RCF), which selects the phase IV (Remedial Action) and phase V (O&M) elements of the Interagency Cost Estimating Group's revised "Phase-based" Hazardous, Toxic and Radioactive Waste (HRTW) Work Breakdown Structure (WBS). It reshuffles them into a three-part cost-reporting format, essentially along the lines of capital and O&M costs.

Costs are presented in Tables 13 through 17 for the following scenarios:

- Hanscom AFB—actual demonstration costs (Table 13) totaling $432,921
- Hanscom AFB—"real world" pilot of same size as demonstration (Table 14) totaling $310,751
- Hanscom AFB—hypothetical full-scale system (Table 15) totaling $3,646,627
- Vandenberg AFB—actual demonstration costs (Table 16) totaling $323,976
- Vandenberg AFB—"real-world" pilot of same size as demonstration (Table 17) totaling $233,624

We note, however, that in our routine practice we are no longer recommending field pilots for CAHs of the type performed here, in which both degradation mechanisms and reagent distribution are tested over a period that can be several years. Rather, tracer testing is performed over a period of 1 to 3 months to define aquifer hydraulics and thus predict reagent distribution prior to full-scale application.

For the actual demonstration cost scenarios (Tables 13 and 16), costs were drawn from the ARCADIS computerized accounting system, which had tracked them on a cost-plus-fixed-fee basis in a series of 20 tasks. Information on the details of the labor, subcontracting, and materials that made up each task total was also reviewed as needed. This project originally considered several other sites in order to downselect to the number of sites at which demonstrations were performed. Thus, costs attributable to the initial planning and investigation for Treasure Island Naval Air Station and Badger Army Ammunition Plant were not included in the calculation. Costs for writing and revising the protocol document were also not included in the calculation. The remaining costs were then mapped as appropriate from the original ARCADIS 20 project tasks into the 23 categories provided in the required format for each of the two sites. A back check was then performed to ensure that all the costs had been allocated but not double-counted.

Then, to calculate the costs of a "real-world" pilot of the same size as the demonstration (Tables 14 and 17), we applied engineering judgment to adjust them to a non-demonstration setting. However, the duration of the injection and monitoring was not changed. Most engineering and

Table 13. Cost Reporting—Cleanup Remediation Technology, Hanscom AFB, Actual Demonstration Costs.

Cost Category	Subcategory	Costs ($)
	FIXED COSTS	
1. CAPITAL COSTS	Mobilization/demobilization	7,646
	Planning/preparation	26,328
	Site work	-
	Equipment cost	
	- Structures	-
	- Process equipment (if purchased)	1,800
	Start-up and testing	-
	Other	
	- Nonprocess equipment	-
	- Installation (wells, background analysis)	
	ARCADIS labor	4,658
	Drilling subcontractor	17,788
	Lab subcontractors	9,785
	Equipment rentals	2,286
	Other subs and expendables	2,526
	- Engineering	13,168
	- Management support	17,712
		103,697
	VARIABLE COSTS	
2. OPERATION AND MAINTENANCE	Labor	113,169
	Materials and consumables	7,807
	Utilities and fuel	-
	Equipment cost (if rental or lease)	7,214
	Performance testing/analysis	25,085
	Other direct costs	
	- Equipment overhead	-
	- Other subs and expendables	8,199
		161,474
3. OTHER TECHNOLOGY-SPECIFIC COSTS	Long-term monitoring,	
	Regulatory/institutional oversight,	
	Compliance testing/analysis*	166,450
	Soil/sludge/debris excavation	
	Collection and control	-
	Disposal of residues	1,300
		167,750
	TOTAL COSTS	
TOTAL TECHNOLOGY COST ($)		**432,921**
Quantity treated (cu yd)		1,200
Unit cost ($/cy)		**361**

* This item is estimated based on 40% of the demonstration's O&M expenditures, 33% of billing costs, and all reporting costs; and it includes 40% of all noncapital laboratory and equipment rental costs.

Table 14. Cost Reporting—Cleanup Remediation Technology, Hanscom AFB, "Real World" Pilot of Same Size as Demonstration*.

Cost Category	Subcategory	Costs ($)
	FIXED COSTS	
1. CAPITAL COSTS	Mobilization/demobilization	7,646
	Planning/preparation	8,651
	Site work	-
	Equipment cost	
	- Structures	-
	- Process equipment (if purchased)	1,800
	Start-up and testing	-
	Other	
	- Nonprocess equipment	-
	- Installation	32,580
	- Engineering	11,852
	- Management support	9,395
		71,924
	VARIABLE COSTS	
2. OPERATION AND MAINTENANCE	Labor	99,007
	Materials and consumables	6,636
	Utilities and fuel	-
	Equipment cost (if rental or lease)	6,132
	Performance testing/analysis	21,323
	Other direct costs	
	- Equipment overhead	-
		133,098
3. OTHER TECHNOLOGY-SPECIFIC COSTS	Long-term monitoring	
	Regulatory/institutional oversight	
	Compliance testing/analysis	104,429
	Soil/sludge/debris excavation	
	Collection and control	-
	Disposal of residues	1,300
		105,729
	TOTAL COSTS	
TOTAL TECHNOLOGY COST ($)		**310,751**
Quantity treated (cy)		1,200
Unit cost ($/cy)		**259**

* Traditional field pilots to test degradation mechanisms are no longer considered necessary for ARCADIS' ERD technology; rather, tracer testing is performed to define aquifer hydraulics prior to full-scale application (see text).

Assumes pilot runs for same duration as demonstration and involves the same number of monitoring events.

Table 15. Cost Reporting—Cleanup Remediation Technology, Hanscom AFB, Full-scale Application*.

Cost Category	Subcategory	Costs ($)
	FIXED COSTS	
1. CAPITAL COSTS	Mobilization/demobilization	15,552
	Planning/preparation	34,603
	Site work	-
	Equipment cost	
	- Structures	-
	- Process equipment (if purchased)	18,000
	Start-up and testing	-
	Other	
	- Nonprocess equipment	-
	- Installation	325,798
	- Engineering	47,406
	- Management support	37,580
		478,939
	VARIABLE COSTS	
2. OPERATION AND MAINTENANCE	Labor	1,485,111
	Materials and consumables	995,393
	Utilities and fuel	-
	Equipment cost (if rental or lease)	91,979
	Performance testing/analysis	213,226
	Other direct costs	
	- Equipment overhead	-
		2,785,709
3. OTHER TECHNOLOGY-SPECIFIC COSTS	Long-term monitoring	212,741
	Regulatory/institutional oversight	56,253
	Compliance testing/analysis	88,284
	Soil/sludge/debris excavation	
	Collection and control	-
	Disposal of residues	24,700
		381,978
	TOTAL COSTS	
TOTAL TECHNOLOGY COST ($)		**3,646,626**
Quantity treated (cy)		148,000
Unit cost ($/cy)		**25**

* Scale-up assumptions:
Application to all of source area as defined in CH2MHill modeling report (approximately 220,000 sq ft)
Application also to a 700'-wide barrier downgradient of sources
Depth of contamination similar to that in the demonstration area; treatment of the intermediate zone only
Injection wells placed on 30-ft centers and in rows 100 ft apart; approximately 100 injection wells required
Drill 15 additional monitoring wells; monitor 25 monitoring wells
Rate of molasses and buffer injection similar to the final, high dosing rates used in demonstration
Injection 3 years, monitoring 5 years total

Table 16. Cost Reporting—Cleanup Remediation Technology, Vandenberg AFB, Actual Demonstration Costs.

Cost Category	Subcategory	Costs ($)
FIXED COSTS		
1. CAPITAL COSTS	Mobilization/demobilization	17,445
	Planning/preparation	26,328
	Site work	-
	Equipment cost	
	- Structures	-
	- Process equipment (if purchased)	1,980
	Start-up and testing	-
	Other	
	- Nonprocess equipment	-
	- Installation (wells, background analysis)	
	ARCADIS labor	20,614
	Drilling subcontractor	23,382
	Lab subcontractors	11,010
	Equipment rentals	5,243
	Other subs and expendables	9,187
	- Engineering	13,168
	- Management support	22,420
		150,777
VARIABLE COSTS		
2. OPERATION AND MAINTENANCE	Labor	50,408
	Materials and consumables	5,841
	Utilities and fuel	-
	Equipment cost (if rental or lease)	5,370
	Performance testing/analysis	20,257
	Other direct costs	
	- Equipment overhead	-
		81,876
3. OTHER TECHNOLOGY-SPECIFIC COSTS	Long-term monitoring,	
	Regulatory/institutional oversight	
	Compliance testing/analysis*	87,494
	Soil/sludge/debris excavation	
	Collection and control	-
	Disposal of residues	3,827
		91,321
TOTAL COSTS		
TOTAL TECHNOLOGY COST ($)		**323,974**
Quantity treated (cy)		237
Unit cost ($/cy)		**1,367**

* This item is estimated based on 40% of the demonstration's O&M expenditures, 33% of billing costs, and all reporting costs; and it includes 40% of all noncapital laboratory and equipment rental costs.

Table 17. Cost Reporting—Cleanup Remediation Technology, Vandenberg AFB, "Real-World" Pilot of Same Size as Demonstration*

Cost Category	Subcategory	Costs ($)
FIXED COSTS		
1. CAPITAL COSTS	Mobilization/demobilization	17,445
	Planning/preparation	8,651
	Site work	-
	Equipment cost	
	- Structures	-
	- Process equipment (if purchased)	1,980
	Start-up and testing	-
	Other	
	- Nonprocess equipment	-
	- Installation	60,550
	- Engineering	11,852
	- Management support	13,612
		114,090
VARIABLE COSTS		
2. OPERATION AND MAINTENANCE	Labor	38,360
	Materials and consumables	4,965
	Utilities and fuel	-
	Equipment cost (if rental or lease)	4,565
	Performance testing/analysis	17,219
	Other direct costs	
	- Equipment overhead	-
		65,109
3. OTHER TECHNOLOGY-SPECIFIC COSTS	Long-term monitoring,	
	Regulatory/institutional oversight,	
	Compliance testing/analysis	50,599
	Soil/sludge/debris excavation,	
	Collection and control	-
	Disposal of residues	3,827
		54,426
TOTAL COSTS		
TOTAL TECHNOLOGY COST ($)		**233,625**
Quantity treated (cy)		237
Unit cost ($/cy)		**986**

* Traditional field pilots to test degradation mechanisms are no longer considered necessary for ARCADIS' ERD technology; rather, tracer testing is performed to define aquifer hydraulics prior to full-scale application (see text).

operations costs were estimated at 85-90% of their actual value. However, planning, management, and reporting costs were reduced more dramatically—typically to 25-30% of their actual value. This calculation predicted that a real-world pilot of the same size and duration as the demonstration would cost between 70-75% of the demonstration. However, as discussed above, in our current commercial practice we would recommend less extensive pilot testing that was more limited in its objectives—focused primarily on distribution issues—thus of much shorter duration and lower cost.

We then scaled-up the real-world pilot costs to estimate a full-scale cost. For brevity, because this site has good conventional remedy cost data and because the level of effort required to reach closure can be easily estimated, we limited this analysis to the Hanscom case. Hanscom has a pump-and-treat system that has been operated for approximately 15 years. The treatment component is air stripping with vapor phase carbon. The pump-and-treat remedy has effectively halted off-site migration and has subdivided the overall plume. However, the concentrations of CAHs at well RAP1-6T in the heart of the demonstration area had not exhibited any consistent trend since 1986. Thus, concentrations in 2000 when the demonstration started were similar to their 1986 values. To prepare this scaled up ERD estimate, we made the following assumptions:

- Application to all of source area as defined in CH2MHill modeling report (approximately 220,000 sq ft).
- Application also to a 700-ft-wide barrier downgradient of sources. This provides treatment of the high concentration portion of the dissolved phase plume and "insurance" should there be gaps in the treatment zone in the source area.
- Depth of contamination similar to that in the demonstration area; treatment of the intermediate lower till zone only (the pump and treat has effectively remediated the surficial aquifer and this demonstration did not target the bedrock).
- Treatment zone 18-in-thick yielding 148,000 cu yd treated.
- Injection wells installed and operated on 15-ft centers and in rows 100 ft apart.
- Install 15 additional monitoring wells; monitor 25 wells (including some of the many existing wells).
- Rate of molasses and buffer injection similar to the final, high dosing rates used in demonstration. Note also that in the 3 years since active demonstration scale ERD treatment was completed at Hanscom AFB, our ERD design and operations philosophy has been refined. Current system designs substantially increase the injection volume while decreasing the concentration of carbohydrate in the injection solutions. This improves the radius of influence and thus coverage of our systems, decreases some secondary effects, and has essentially been cost neutral.
- Treatment over 4 years, monitoring over 5 years but with monitoring events much more widely spaced in time than those in the demonstration. The demonstration system was operated for 2 years, and data has been reported to ESTCP for 41 months (see a separate report on rebound monitoring on ESTCP's website).
- Costs for years 2-5 were corrected to net present value using a 4% per year discount factor.
- Per ESTCP guidance, no inflation or escalation was included.

- Treatment of the entire plume to MCLs is not assumed. Rather, a risk-based closure is anticipated that includes natural attenuation (see protocol Section 6.5, Suthersan 2002, and Demonstration Plan Sections 1.3 and 5.1).

The uncertainty of these estimates depends on scale. The actual demonstration costs, at least at the bottom line level, should be very accurate, certainly within 5%. The characterization/ breakdown of actual demonstration costs into the various elements of the WBS has more uncertainty. The estimate for a "real world pilot of the same size as the demonstration" should be accurate to within 10%. The estimate for full scale is much more uncertain since a full engineering design of such a system is not within the scope of this project. We estimate this uncertainty at 30%.

5.1.2 Cost Comparison to Existing Site Remediation System at Hanscom AFB

The Operable Unit 1 (OU-1) plume, which is the target of this demonstration, is the primary, though not the only cost of restoration work at Hanscom AFB. An AFCEE Remedial Process Optimization report from 2000 complimented the base staff, namely Tom Best, for his excellent work in "improving the effectiveness and efficiency of his program." Thus, this pump and treat can be viewed as well run, and thus a fair comparison for alternative technologies. The AFCEE report estimated the OU-1 cost to complete at $11.3 million with an annual operating cost of $500,000 per year through 2025. Based on $500,000 per year, 4% discount rate, from 2005-2025 we calculate the net present value (NPV) for the future O&M of this pump-and-treat system to be $7.02 million. The second 5-year review report for Hanscom AFB provides very detailed operating costs for the OU-1 remedial action operations from April 1991 through February 2003, which total $6,410,739. This includes both basic O&M and such maintenance actions as acid washing towers, repacking towers, and various equipment upgrades. This doesn't include energy costs, which were estimated at $96,000 for FY 02. Tom Best (Hanscom AFB) provided information showing that the construction and design costs for the OU-1 system were at least $6.7 million (incurred in 1988-91). The FY 2000 Defense Environmental Restoration Program (DERP) Report to Congress shows that to date, $30.3 million had been expended on environmental restoration at Hanscom with a cost-to-complete of $15.2 million (not all on OU-1 although OU-1 is a significant part). The corresponding figures from the FY 2004 DERP report were expended to date (all of Hanscom) $35.3 million and cost-to-complete $10.4 million (through 2020).

Thus the life-cycle cost of the Hanscom OU-1 pump-and-treat system can be estimated as follows:

- Capital/start-up cost of original system in 1988-1991: $6.7 million
- O&M and upgrade costs April 1991-February 2003: $6.4 million
- Estimated O&M cost for 2003 and 2004 based on 2002 value: $0.88 million
- Energy costs 1991-2005 based on 5-year report figure for FY 02 ($96,000) adjusted for inflation at 4% per year: $1.25 million
- Estimated NPV for future O&M 2005-2025 based on AFCEE report: $7.02 million
- Total Life-Cycle Cost: $22.3 million

There are significant uncertainties in comparing the cost of the pump-and-treat system to the demonstrated technology:

- The pump-and-treat system has removed mass over its approximately 15-year operating history that no longer needs to be removed. However, concentrations in the demonstration area had not decreased in the 10 years the pump and treat was operated before the demonstration started.
- Current cost estimates for pump and treat are based on operation through 2020 or 2025, but there is no certainty that pump and treat will reach remedial goals by that time. It would be reasonable to anticipate that at best the pump-and-treat system would reach some asymptote when concentration reduction and mass reduction would become small.
- We prepared an ERD estimate based on treating the OU-1 lower aquifer that was the subject of the demonstration only. The pump-and-treat system that was operated affected the shallow aquifer as well as the lower aquifer.

However, it does appear that the ERD technology, whose full-scale implementation for the lower aquifer was estimated at $3.6 million, should be considerably more economical than the pump and treat remedy, whose life-cycle cost is $22.3 million.

5.1.3 Other Cost Data for ERD Technology—Commercial Sites

Extensive information about cost experience in actual practice with this technology has been provided in Appendix A of the protocol document (Suthersan, 2002, Table A-5) and in Appendix E-11 of the recent “Principles and Practices of Enhanced Anaerobic Bioremediation of Chlorinated Solvents” report (Lutes et al, 2004, page E-11.9). These costs are broken down into capital and O&M costs with initial concentration of contaminant and size of plume information.

A detailed cost breakdown for a Wisconsin full scale site with capital costs of $380,000 and annual O&M costs of $85,000 and a total cost of $550,000 has been published in a DoD document (Frizzell et al, 2004). Remediation at this site was dramatically successful, leading to regulatory approval for site closure. No rebound was observed.

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 million for a large plume treatment with a fully automated reagent injection system. Table 18 presents a selection of cost examples with concentration and size information. The full-scale system for the automated site included installation of more than 100 reagent injection wells to provide aggressive plume-wide treatment.

Operating costs (including reagent injection, monitoring and reporting) have generally been 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.

Table 18. 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 Pennsylvania	$75,000	$45,000	$250,000	46,000 µg/l PCE	10,000 ft^2 x 20 ft deep
Uranium processing facility, Eastern United States	$480,000	$65,000	$760,000	5 – 14,000 µg/l PCE (plus U)	19.3 acres or 1,200 x 700 ft
Former metal plating site, Western United States[1]	$100,000	$150,000	$250,000	24,000 µg/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 µg/l CT, chloroform, TCE	3.25 acres or 141,600 ft^2 x 10 ft deep
Industrial site, Northeastern United States	$150,000	$80,000	$750,000	120 µg/L PCE	3,000 ft long in bedrock, depth varies
Former dry cleaner, Wisconsin[2]	$200,000	$100,000	$400,000	1,500-4,000 µg/L PCE	30,000 ft^2 x 5 ft deep
Former automotive manufacturing site, Midwestern United States	$75,000	$60,000	$375,000	800 µg/l TCE	1,000 x 400 ft x 20 ft deep
Area of Concern (AOC) 50, Fort Devens, Ayer, Massachusetts	$150,000	$150,000	NA[3]	4,000 µg/L PCE	3,000 x 400 ft x 40 ft deep

Notes:
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.

The cost data presented in Table 18 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.

However, the reader should note that the examples in Table 18 necessarily represent relatively early applications of the technology. As such, we expect them to be lower in cost than some future applications, because as the field has developed and our confidence has grown, more difficult sites are being treated. Specifically, early applications of the technology tended to be sites with dissolved phase plumes and sorbed mass while current applications include sites with more significant source material that can require longer treatment periods.

5.1.4 Costs of Full-Scale Remediations, Including ERD Technology at Federal Sites

The technology has also advanced in recent years through guaranteed, fixed-price remediation (GFPR) contracting. GFPR creates an environment through which ERD and other innovative technologies can be rapidly applied to achieve site closure and unrestricted land use. GFPR creates an innovative contracting environment that incentivizes cost savings and innovation. The technology has now been fielded at 21 federal sites at 16 facilities, and ARCADIS is under contract or in regulatory negotiations for implementation at another 6 federal sites at 4 facilities (see Table 19). Table 20, which was prepared originally by the Army Environmental Center, shows the savings that has been achieved at Army GFPR sites. Note that the data in this table is not a pure comparison of the cost of ERD to conventional technologies because:

- The services included in the GFPR contracts typically cover multiple sites and media, only a subset of which are being treated with ERD. However, in the cases where ERD is being used as one of the remedies for a facility (blue shading on table), it is often being used on the most costly operable units.
- Services under a GFPR contract are not just innovative remediation. Additional site investigation, regulatory negotiation, and maintenance of existing remedial systems are usually included.
- The costs are compared to a government cost to complete budgetary estimate. These estimates are subject to various sources of error.
- The remediations in these cases have usually not been completed; however, the contract cost values represent a guaranteed, insured cost for achieving the milestones (typically closure). As such, they often include the costs attributable to risks such as unknown contaminant concentrations that are not included in conventional estimates for baseline technologies.

Nevertheless, Tables 18 and 19 show that this technology has already been widely used at full scale to provide cost savings to DoD.

5.1.5 Other Cost Comparisons Between ERD Technology and Baseline Technologies

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 at

Table 19. Federal IRZ Sites at ARCADIS.

Active/Proposed	Federal Facility	Location	Number of Sites	Type of Contract/ Funding: Technology Demonstration	Type of Contract/ Funding: Standard Environmental Contract	Type of Contract/ Funding: Guaranteed Fixed Price	Scale of Application: Bench	Scale of Application: Field Pilot	Scale of Application: Full-Scale	Status
Active or completed IRZ sites	Naval Weapons Industrial Reserve Plant	Dallas, TX	1		X			X		Successfully completed
	Hanscom Air Force Base	Bedford, MA	1	X				X		Effective CAH removal in a source zone
	Sierra Army Depot	Herlong, CA	4			X		X		Ongoing
	Vandenberg Air Force Base	Lompoc, CA	1	X				X		Demonstration successfully completed
	AHTNA/ACOE (Fort Ord)	Monterey, CA	1			X		X		Successfully completed
	Fernald Environmental Management Project	Cincinnati, OH	1		X		X			Bench tests complete for Uranium removal
	Former US Disciplinary Barracks	Lompoc, CA	2		X	X		X		Ongoing (TCRAs)
	Fort Devens	Devens, MA	1			X		X		Successfully completed; full-scale planned
	Jet Propulsion Laboratory	Pasadena, CA	1	X				X		Successful perchlorate removal
	Fort Leavenworth	Leavenworth, KS	2			X		X		Ongoing
	Charleston Air Force Base	Charleston, SC	1			X		X		Ongoing (IRM)
	Fort Jackson	Columbia, SC	1			X		X		Startup August 2004
	Confidential	CA	1							System installation planned for summer 2005
	Ramstein Air Base	Germany	1		X			X		Barrier planned; pilot startup early 2005
	Fort Gordon	Augusta, GA	1			X			X	Well installation underway; startup June 2005
	Milan Army Ammunition Plant	Milan, TN	1			X		X		Ongoing for explosives
Under contract/ regulatory proposal	Kaiserslautern Army Depot	Germany	1		X			X		In planning stages
	Reese Air Force Base	Lubbock, TX	1			X		X		Proof-of-concept planned
	Vandenberg Air Force Base	Lompoc, CA	1		X				X	In planning stages
	Lake City Army Ammunition Plant	Independence, MO	3			X		X		In planning stages

Table 20. Demonstrated Savings (Cleanup via Performance-Based Contract at Active & BRAC/Excess Installations; adapted from Army Environmental Center data)*

Installation	Type	CTC ($M)	Awarded ($M)	Savings ($M)
Camp Bonneville, WA	BRAC	5.02	5.40	(0.38)
Camp Pedricktown, NJ	BRAC	2.73	2.88	(0.15)
Fort Devens (AOC 50), MA	BRAC	8.40	7.96	0.44
Fort Dix, NJ	Active	6.00	3.80	2.20
Fort Gordon, GA	Active	20.40	19.40	1.00
Fort Jackson, SC	Active	9.80	14.20	(4.40)
Fort Leavenworth, KS	Active	21.80	19.87	1.93
Fort Pickett, VA	BRAC	3.50	2.95	0.55
Fort Sheridan, IL	BRAC	20.23	17.15	3.08
Fort Ord (OU 1), CA	BRAC	6.34	5.71	0.63
Hingham Annex, MA	BRAC	1.92	1.97	(0.05)
Lake City AAP, MO	Active	68.20	52.40	15.80
Lompoc Disciplinary Barracks, CA	BRAC	4.40	3.80	0.60
Milan AAP, TN	Active	58.5	45.6	12.9
Ravenna AAP, OH	Excess	12.00	9.80	2.20
Rio Vista, CA	BRAC	5.06	3.76	1.30
Sierra Army Depot, CA	Active	27.70	19.30	8.40
TOTAL		**282**	**235.95**	**46.05**

***Using Performance-Based Contracts resulted in an overall 16.3% cost savings compared to the CTC (cost-to-complete) estimates.**

Green shading indicates Army PBCs being performed by ARCADIS that don't include IRZ.
Blue shading indicates Army PBCs being performed by ARCADIS that do include IRZ.
No shading indicates Army PBCs being performed by others.

commercial sites with ERD technology. Examples of actual and projected savings associated with these sites are listed in Table 21. The geometries of the listed CAH sites are intercomparable, being generally plume-wide or multiple-transect applications (as opposed to single linear containment barriers) and not solely source area hot spot treatments. These CAH sites also generally fall into the category of dissolved phase plumes with sorbed source material.

5.2 COST ANALYSIS

5.2.1 Major Cost Drivers

This section provides a general discussion of cost factors associated with ERD, a subject that is covered in more detail in the Vandenberg final report, Section 2.3 (ARCADIS 2004). An even more extensive discussion of ERD cost drivers has recently been published as Sections 4 through 6 of the protocol document (Suthersan et al, 2002).

In general, CAH plumes in groundwater may take several forms:

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

Although application of ERD can occur in various 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. Site screening criteria and methods are discussed more fully in Section 2 of the protocol document (Suthersan et al, 2002), and an updated discussion of this topic is available as Section 4.1 of Suthersan 2005.

For the soluble carbohydrate ERD technology, 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 22. The selection of carbohydrate substrates 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.

Most 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, when sized for use at a typical pilot test site, can be mobilized to

Table 21. 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 22. Relative Costs of Various Electron Donors.

Electron Donor	Bulk Price $/lb of TOC	$/lb of PCE Treated
Molasses	0.20 – 0.35	0.16
Sugar (corn syrup)	0.25 – 0.30	0.4
Sodium Lactate	1.25 – 1.46	NA
Whey (powdered, dry)	1.17	NA
Whey (fresh)	0.05	0.04
Edible oils	0.20 – 0.50	NA
Flour (starch)	0.3	0.85
Cellulose	0.40 – 0.80	NA
Chitin	2.25 – 3.00	NA
Methyl cellulose	4.00 – 5.00	NA
HRC™ (Regenesis commercial material)	5.00 – 6.00*	NA

NA - Not analyzed
*Personal Communication, Leeson, 2002

each site in a conventional pick-up truck or trailer. Larger injection volumes are typically used for full-scale injection and can be obtained premixed/diluted and delivered in tank trucks. 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.

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. Four 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 and maintenance costs) and the more time it takes for reagent delivery.
- *Depth of target zone*—Injection well installation and maintenance 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 the base of the contaminant zone 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-ft screened interval represents a practical maximum 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 ft.
- *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, as with deep settings or complex geology. In such cases, an in situ recirculation well can yield considerable cost savings over direct injection wells. The 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.
- *Monitoring Cost*—The biogeochemical monitoring program used in this demonstration and discussed in Section 3 of the protocol document and in Section 4.4 of Suthersan 2005 can be a significant component of project cost. Recently we have been recommending that routine operational system monitoring be

conducted with a much more focused list of parameters such as CAH concentration, TOC, pH, and methane/ethane/ethene only.

5.2.2 Sensitivity Analysis

The baseline for the sensitivity analysis is the hypothetical Hanscom AFB full-scale system, which has a 3-year injection program with a total of 5 years of monitoring. Injection wells are placed on 30-ft centers and in rows 100 ft apart. There is a 700-ft-wide barrier downgradient of sources with wells in line on 30-ft centers. In this scenario, the number of wells needed is 220,000/(30X100)+700/30 = 97 wells (rounded to 100 for cost estimation).

ARCADIS conducted two separate sensitivity analysis exercises based on this scenario, each varied one key input to two alternate values. First, the injection and monitoring times were varied to 2-year injection and 3-year monitoring, as well as 5-year injection and 8-year monitoring. Second, the well spacing was changed to 15-ft centers and then to 45-ft centers. With well spacing of 15 ft, a total of 193 wells was needed; and, with well spacing of 45 feet, 64 wells were needed. Each scenario was discounted for net present value in a manner similar to the base case. Discounted costs are included in the following table.

Number of Injection Years, Monitoring Years	Well Spacing (ft)	NPV Discounted Cost (US$)
3, 5 (baseline)	30 (baseline)	3,502,199
1, 2	30	2,598,338
5, 8	30	4,784,496
3, 5	15	6,102,182
3, 5	45	2,495,754

This shows that the period of injection and monitoring as well as well spacing are strong cost drivers.

5.2.3 DoD-Wide or Agency-Wide Savings

Commercial cost savings for ERD technology as compared to conventional technologies have been documented in Table 21 and range from $200,000 to $6,400,000 per site (50-75% savings). The cost comparison for Hanscom above suggests that, if ERD had been available for use before the pump and treat infrastructure was installed, it might provide a savings of $8-13 million (35-60%), depending on the assumptions made on the lower and bedrock aquifers.

Historical application costs for the ERD technology, as listed in Table 18, range from $250,000 to $2,000,000 for sites up to 28 acres. As confidence is gained with the technology, however, more difficult, expensive sites are being treated; target concentrations/masses of CAH are increasing; and bedrock treatment is becoming more common. Some indication of the typical remediation cost for chlorinated solvent sites can be obtained from EPA, 2004 (Exhibit 12-2), which lists an average of $402,000 for 50 dry cleaner sites (typically among the smallest CAH sites) and at least $6 million (discounted) for a typical National Priorities List (NPL) pump-and-treat site (pages 14-12). NPL sites are traditionally believed to include some of the largest and most complex sites. EPA, 2004 (pages 6-14), estimates that there are 9,060 total DoD sites requiring remediation (including 2,664 with cleanup planned or underway) with a cost to complete of $16.4 billion. That would suggest a typical cost to complete for a DoD site (not total life-cycle cost) of $1.8 million. Therefore, based on all these data sources, it is estimated that a typical DoD CAH site has a life-cycle cost of remediation of $2.5 million. Obviously, at $22.3 million life-cycle cost, Hanscom OU-1 provides an example that suggests that $2.5 million for a typical site may be low.

As of 2003, Harre and Henry estimated 253 Air Force and 450 Navy CAH sites. The number of Army CAH sites isn't reported by Harre and Henry but can be estimated as at least 300 based on EPA, 2004, which shows 696 Army groundwater VOC sites. Thus, at least 1,003 CAH sites exist in DoD. However, the figure of 1,536 to 2,368 DNAPL sites in DoD provided in Exhibit 14-3 of EPA, 2004, would suggest that this number is low.

It would be reasonable, based on our commercial and DoD experience, to assume that this technology could be applied at more than 50% of all groundwater CAH sites. Thus, an estimated savings from application of this technology would be: (0.5 fraction of sites treated X 1003 sites X $2.5 million typical site cost X 0.5 savings) = $626 million potential savings DoD-wide.

5.3 COST COMPARISON

5.3.1 Cost Comparisons Versus Baseline Technology—Pump-and-Treat System

This information is provided in Sections 5.1.2 and 5.1.3.

5.3.2 Cost Comparisons Versus 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 23). The site contained a dissolved PCE/TCE plume in low-permeability, saprolitic soils. The comparison favorably portrays the application of ERD technology 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' ERD technology), an in situ permeable reactive barrier incorporating zero valent iron, and a pump-and-treat system with air stripping and carbon adsorption.

Table 23. 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

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 remediation. The results of the evaluation from Quinton et al are summarized in Table 24.

With the assumptions made during the DuPont evaluation, substrate-enhanced biobarrier (comparable to ARCADIS' ERD 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 ERD 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, with the exception of natural attenuation.

Cost will certainly depend on scale, and generally the cost of the ERD 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.

Table 24. Results of DuPont Technology Evaluation.

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

From Quinton et al, 1997

6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

In general, the cost of ERD is quite competitive with other in situ bioremediation technologies, as discussed in Section 5.3, in that the cost of the reagent itself (molasses, corn syrup, and some forms of whey) is low relative to most other electron donors in current use. A comparison of costs for a variety of different reagents is given in the final technical reports for the two demonstrations. The most sensitive cost elements for this technology include:

- Formation depth (cost increases with increasing depth)
- Treated volume (cost increases with increasing volume)
- Injection well spacing (cost decreases with increasing spacing)
- Flux of energetically favorable electron acceptors into the reactive zone (i.e., oxygen, nitrate, iron) (cost increases with increasing flux)
- Time of operation, which in turn is governed by the strength of the sorbed or non-aqueous source term (cost increases with increasing time of operation)
- Required frequency of injection

The costs of the Hanscom and Vandenberg demonstrations were affected by unforeseen hydrogeological and biogeochemical factors discussed elsewhere, which prolonged their duration. Compared to the cost of typical non-demonstration applications under similar conditions, the costs of the demonstrations were higher because much more detailed monitoring was conducted for demonstration purposes. Costs of individual monitoring events and costs associated with the duration of pilot tests can be dramatically lower in typical field applications. For instance, after the baseline biogeochemical environment has been characterized, the monitoring program can in many cases be reduced to as few as four key parameters—VOCs, TOC, pH, and light hydrocarbons. Also, under appropriate conditions and regulatory approval, labor-intensive, low-flow sampling methods can be replaced by passive diffusion bag sampling. Other areas of cost savings and performance enhancement have continued to develop as the technology has matured, as it has since this demonstration project was planned. For example, the objectives of a typical field pilot test that we perform today are generally geared toward defining reagent distribution parameters rather than demonstrating complete dechlorination at pilot scale. As such, pilot tests are typically conducted primarily with tracer and completed in a few months, as compared to the duration of these demonstrations of more than 2 years.

6.2 PERFORMANCE OBSERVATIONS

System performance relative to performance objectives is summarized in Tables 10 and 11. In brief, the Hanscom demonstration was successful in achieving the performance criterion for TCE. Criteria for TCE daughter products were not attained during the initial year 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, and suggesting that remediation of TCE daughter products to MCLs could also be achieved using ERD technology. By 17 months after the end of active treatment, the baseline concentrations of TCE, cis-DCE, and VC had been reduced at the most highly treated wells by 97 to >99%. No rebound of CAH concentrations had occurred as late as 17 months after the last injection; rather, effective treatment appeared to be continuing (see www.estcp.org for a supplemental report of Hanscom rebound monitoring data). Furthermore, the demonstration area was in a source zone; thus long-term effectiveness in a source zone was observed for enhanced in situ biodegradation.

The Vandenberg demonstration was initially hampered by the low buffering capacity of the aquifer, which caused pH to be depressed to levels below the desired operating range. However, after a buffer was implemented, more reagent was delivered, and system performance improved. Although the quantitative goal of 80% reduction in total CAHs with 1 year was not attained, reductions in TCE concentrations were ≥ 80% at the most highly treated monitoring wells. Multiple lines of evidence of complete treatment—production of ethene, reduction in cis-DCE, and no accumulation of VC—were seen in the most effectively treated downgradient wells. Effective treatment of CAHs continued at most of the reactive zone wells after the last injection, and in some cases was even enhanced by recovering pH levels. No rebound of TCE was seen as of 16 months after active treatment.

6.3 SCALE-UP

Scale-up issues were anticipated to be (1) efficacy of the manual batch injection mode and (2) determination of area of influence. Batch injection was proven successful at both sites. Area-of-influence was not closely defined in the Vandenberg demonstration due to the continued growth of the reactive zone beyond the monitoring well network, but an estimate was made for Hanscom (see Section 4.3.6.1 of ARCADIS, April 2004).

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.

At least 33 full-scale applications of this technology using a variety of injection modes and geometries have been reported (Suthersan and Payne, 2005; Lutes et al, 2004a, Lutes et al, 2004b).

6.4 OTHER SIGNIFICANT OBSERVATIONS

Experience with scores of ERD sites has shown that a key to successful treatment with ERD (or any other in situ remedy involving dispersal of reagent) is distribution of the reagent. Thus, a major focus of our ongoing enhancement of the technology is on understanding the flow direction and travel time of the reagent as well as its dilution by the immobile fraction of pore water and inflow from upgradient areas. New methods of aquifer testing using tracers have been developed to address the hydraulic issues that are of specific interest to ERD.

This technology is covered by U.S. Patent Nos. 5,554,290; 6,143,177; 6,322,700; and 6,562,235.

For information on working with ARCADIS at federal sites, contact Chris Lutes at 919-544-4535; for commercial sites, contact Suthan Suthersan at 267-685-1800.

6.5 LESSONS LEARNED

Some specific lessons learned from the Hanscom and Vandenberg demonstrations are included below.

Substrate Dosing Required for Successful Treatment

Successful treatment was usually associated with TOC values between 10 and 200 mg/L at Hanscom, and a wide range, between 10 to 3,000 mg/L at Vandenberg. In comparison to the guidance in the protocol document (Suthersan et al, 2002, Section 4.5), based on observations at many sites, that 50-200 mg/L TOC in monitoring wells is sufficient for complete degradation, the demonstrations illustrate the wide variability of site responses to dosing rate. Demonstration results further suggest that methanogenic conditions as indicated by methane concentrations in excess of 1,000 µg/L are generally associated with expedited treatment.

Optimization Time Required

Most ERD pilot systems have been operated for a period of 6 to 18 months to gather the information needed to determine whether and how to scale up the system (Lutes et al, 2004a; Suthersan 2002). However, at Vandenberg, which was a 26-month program, optimization time was prolonged primarily by buffering issues. More recently ARCADIS has been focusing pilot-scale efforts purely on rapid collection of reagent distribution information needed for full-scale design. All treatment systems, whether pilot-scale or full-scale should be designed to facilitate rapid adaptation to changing conditions and new information during the operational period. This "adaptive design" approach is especially important in enhanced in situ bioremediation technologies such as that discussed here, which are often operated for several years (Suthersan and Payne, 2005, Sections 2.3.1.7 and 4.8.2).

Long Lag Times to Complete Dechlorination

The lag time to complete dechlorination can be significant. Vandenberg represents a relatively long lag time for ERD, both because it was initially aerobic and because of buffering issues. Remedies for both conditions are well documented within this report. During the pilot testing phase, it is important to define and address any conditions that may delay the onset of complete dechlorination.

Fermentation and By-Product Formation

The formation of undesirable by-products, 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 by-products are generally limited in extent and often sporadic in nature. It is expected that these ketones are also utilized by microbes in the IRZ, and, being readily aerobically degradable, 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 producing these by-products needs to be accounted for in the project planning stage. Although ketones were generated during the demonstration as metabolic by-products of molasses degradation, they did not pose appreciable risks.

Pilot Test Design

At the Hanscom site, where one injection well was used, substantial variability in the groundwater flow direction vector resulted in marked changes over time in the substrate concentration at the most affected downgradient monitoring wells and insufficient impact at other wells. 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 is less subject to changes in the groundwater flow direction vector, and more likely to maintain strongly reducing conditions in a central location.

Treatment Varies Within the Reactive Zone/Size and Shape of Reactive Zone Varies

Both sites show that treatment varies within the reactive zone. At Hanscom, there was a clear demarcation between wells that received substantial doses of carbohydrate (TOC), which showed dramatic treatment effectiveness, and wells that received little or no sustained carbohydrate (TOC) and showed little or no treatment. The size of the treated area from the single injection well used was not fully delineated due to limitations on funding and the fact that the actual flow direction was more northeasterly than originally anticipated during design. Flow direction also varied due to the effect of variable downgradient pumps not controlled by ARCADIS. Our current engineering practice is to use one or more tracer tests (either bromide or carbohydrate) during pilot testing to gather information about distribution variables, including flow direction and radius of influence. During full scale operation, we currently adjust TOC dosing as needed to maintain a measurably increased level of TOC 100 days travel time downgradient of the injection well. If such a flow direction change did occur in a full-scale system treating a defined source zone area, with injection wells laid out on a grid basis (the scenario discussed for Hanscom scale-up), the effects of modest changes in flow direction would be minimized. In that case the reactive zones produced by each injection well would be shifted but would still lie within the source zone in almost all cases. However there would be one edge of the targeted zone where either revised pumping strategies, increased radial injection volume, or additional wells would be needed to cover the area "uncovered" by the flow direction change. Such flow direction changes/errors can be more costly for barrier systems if they occur on a macroscale, and thus the design of barrier systems needs to incorporate careful flow measurement.

At Vandenberg AFB we noted that the dispersion from three parallel injection wells nominally installed in the same hydrogeology varied dramatically. Such variations are to be expected in full-scale systems and thus the design and operations of the system must be “adaptive.” In this case, the volume and concentration of the injection solution and the frequency of injection was adapted. As discussed in a previous section our current operational philosophy utilizes larger injection volumes than were used at Vandenberg, which would help overcome such localized differences in dispersion.

At Vandenberg AFB, though adequate carbohydrate dosing (TOC) was sustained at some monitoring wells (i.e., MW-20 and MW-16) consistently throughout the demonstration period, at other wells (e.g., MW-11 and MW-7) increased TOC was observed at adequate concentrations after an initial delay attributable to advective flow, but then declined over time toward the end of the active treatment period. Such behavior has been observed at many other sites and can be explained by an increase in the microbial populations that consume the injected carbohydrate. This is another condition to which system design must be adapted as the project continues. In this case, had the operations period continued longer, it would have been appropriate to increase the volume injected or perhaps the mass of carbohydrate injected to better influence these wells.

Our conceptual understanding of the structure of systems in which a substrate/electron acceptor is introduced into an aquifer supports the existence of a redox recovery zone downgradient of the reactive zone. (This concept is discussed for landfills in Smith, 1997; for petroleum hydrocarbon releases in Rice et al, 1995; and for anaerobic reactive zones in Suthersan et al, 2002, Sections 4.5, 6.5, and 7; and Suthersan and Payne, 2005, Sections 5.3.2 through 5.3.4). Since reactive zones function as biological reactors with several different metabolic zones, it follows from engineering fundamentals that the most complete treatment will not be observed at the upgradient edge of the reactive zone, nor in the middle of the zone, but rather at the downgradient edge of the reactive zone and/or in the further downgradient "redox recovery zone." We expect, based on other studies, that these zones are important in controlling secondary water quality effects and in providing additional removal of vinyl chloride (see review in Bradley, 2003). Thus while it is appropriate to monitor wells within the reactive zone to understand and adjust the operation of the system (as was done at Hanscom and Vandenberg), the primary focus of compliance monitoring in full-scale systems should be downgradient of the reactive zone.

Application in Areas of High Constituent Concentration/DNAPL

Although it was not originally designed as a study of source zone treatment, evidence from the Hanscom site suggests that this demonstration was successfully operated in a source area. One benefit of applying ERD in high concentration regimes is related to the enhanced mass solubilization that is often observed with this technology (Suthersan and Payne, 2005, Sections 2.3.1, 5.2.3, and 5.6.2). When the groundwater equilibrium is altered, the transfer of more constituent mass from the free or adsorbed phase into the dissolved phase often occurs, resulting in an increase in the treatable soluble portion of the total CAH mass. This effect can be used alone 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 these effects do not result in the migration of elevated dissolved concentrations away from the treatment area.

Secondary Water Quality Impacts

Secondary water quality impacts (including metals mobilization, high COD/BOD, and generation of ketones) 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 at both sites as metabolic by-products of molasses biodegradation, they did not appear to pose an appreciable risk.

Groundwater Chemistry Impacts

As seen at Vandenberg, the geochemical impacts of the ERD, i.e., the zones of redox, TOC, and bromide impacts, may extend farther downgradient than the zone of effective treatment. One of the goals of pilot testing is to determine the extent of such impacts so the design for the full-scale system spaces injection wells at an appropriate distance from potential downgradient receptors such as surface water bodies.

6.6 END-USER ISSUES

Site contacts for the demonstrations were Tom Best at Hanscom AFB, and Amena Atta at Vandenberg AFB. Both have expressed satisfaction with the results of the demonstrations. ERD has in fact been proposed for a separate site at Vandenberg. A workplan is under review by the California Regional Water Quality Control Board.

The results of the demonstrations were used to develop a protocol for the use of ERD technology for CAHs at DoD facilities, entitled "Technical Protocol for Using Soluble Carbohydrates to Enhance Reductive Dechlorination of Chlorinated Aliphatic Hydrocarbons" (Suthersan et al, 2002, published on a SERDP/ESTCP website).

Stakeholders and end users of ERD technology are generally 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 production of gases, intermediate products of dechlorination, and secondary water quality impacts from ERD applications is expected within the reactive zone and is also of potential concern to stakeholders and regulatory agencies. Adaptive design and operations approaches are needed to allow full-scale system operators to manage groundwater flow direction/velocity changes. None of these issues should be considered major impediments to technology implementation but must be considered in the design of each project. Secondary water quality impacts (including metals mobilization, high COD/BOD, and ketones) were observed at the demonstration sites, but as expected were limited to the areas of the reactive zones and did not appear to be significant downgradient. A potential end user issue is that the reducing conditions induced by substrate injections persisted, at least at Hanscom, for a substantial period. Although this could be a benefit in cases where long-lasting treatment is desired, it could also be a detriment in cases where the groundwater within the reactive zone needs to return rapidly to aerobic conditions to support a planned immediate use. Further in-depth discussion of these issues is provided in:

- Section 4.3.5 of the Hanscom Final Report (ARCADIS, 2003)
- Section 4.3.5 of the Vandenberg Final Report (ARCADIS, 2004)
- Section 5.3.4 of Suthersan and Payne, 2005.

6.7 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

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 this technology. However, the technology has been successfully permitted in numerous jurisdictions and the regulatory community's experience base is growing. ARCADIS has ongoing or completed IRZ projects in 32 states. 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. 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.

Potential concern regarding secondary water quality issues and rebound have been extensively discussed in other sections of this document and the protocol.

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APPENDIX A

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