# Cyclodextrin Enhanced In-situ Removal of Organic Contaminants from Groundwater at Department of Defense Sites

## - Final Report –

**prepared by**

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# Executive Summary

Funded by the Environmental Security Technology Certification Program (ESTCP), this technology demonstration was intended to show the potential of cyclodextrin enhanced flushing technology (CDEF) under full-scale operational conditions. The particular objectives of this demonstration were (1) evaluation of the cost and performance of cyclodextrin (CD) enhanced removal of dense nonaqueous phase liquids (DNAPL) from polluted groundwater, (2) testing unrefined, liquid CD as substitute for CD powder, (3) evaluate membrane technology for recovering and reusing CD, (4) identifying most appropriate wastewater treatment technology(-ies), and (5) conducting partition tracer tests (PTT) for mass balancing. This project was intended as a technology demonstration only – the remediation of the entire test site was not an objective.

The overall duration of the demonstration was 4 months, during which approximately 32.5 kg TCE and 1,1,1-TCA plus an estimated 3 kg of 1,1-DCE and an unknown amount of other contaminants were removed (total DNAPL volume removed: ca. 30 liters). The resulting decrease in DNAPL saturation was approximately 70% to 81%. The principal performance measure for DNAPL removal were partition tracer tests conducted before and after the CDEF tests and mass balance calculations based on the amounts of recovered VOC contaminants. TCE concentrations in the reference wells declined between 38.5% to 99.4% (average: 77.3%) from their pre-CDEF levels.

Liquid, technical grade CD has been demonstrated to perform equally well than the more expensive powder CD tested during previous field applications. Further, CD solution recovered from the subsurface was reused after treatment without indications of decreased removal effectiveness. An ultrafiltration (UF) system was capable re-concentrating recovered CD solution from 5% to 20% (wt/wt), but the treatment capacity of the UF used during this demonstration was low and prevented continuous in-line operation.

A conventional air stripper and a pervaporation system (PVP) were tested. Although full assessment of the PVP was prevented due to damages that could not be repaired in the field, it achieved higher contaminant removal rates (99%) compared to the air stripper (90%). The operation of the PVP system required a dedicated field technician and consumed large amounts of electrical energy. In addition, the pervaporation process creates a highly VOC enriched effluent that must be disposed of. In comparison, the air stripper was much easier to operate and required little maintenance, i.e. removal of iron precipitates. Also, much less energy was consumed running the air stripper.

The cost of the CDEF technology was evaluated based on two principal application schemes: injection/extraction of CD solution using several injection and extraction wells (I/E test) and application of CDEF in push-pull mode (CPPT). The I/E test was conducted by injecting 20% CD solution in dedicated injection wells. After passage through the DNAPL source zone, the flushing solution was recovered from a number of extraction wells, treated, and then reinjected. During push-pull application, a slug of 20% CD solution was injected into and extracted from a well. The extracted flushing

solution was reconditioned (i.e. the CD concentration was readjusted to 20%) and then reinjected again. Up to three wells were treated this way at the same time. With regard to the cost of these treatment approaches, several full-scale cost estimates were developed. Overall, the CPPT approach generated only half the cost of a comparable I/E system. Because much of the CD used during CPPT treatment was recovered and reused, full-scale cost analysis were performed for two CPPT cases (a) UF in operation and (b) without an UF. The results indicated that, at least during this demonstration, a UF system did not necessarily decrease the cost of CDEF. However, even comparably small enhancements of the UF process would favor the UF reconcentration approach.

Although many unexpected problems were encountered, e.g. less than expected performance of the membrane filter system and subsurface heterogeneities that affected the well field geometry and flow field hydraulic performance, the results of this demonstration clearly revealed that CDEF technology increased the rate of DNAPL removal relative to conventional water flushing.

# Acknowledgements

We thank the *Environmental Security and Technology Certification Program*, ESTCP, for supporting the cyclodextrin enhanced flushing technology demonstration. Additional support, in kind, was received from the Naval Amphibious Base Little Creek (NABLC).

Many people have contributed to the success of this demonstration. Our special thanks go to the Naval Amphibious Base, Little Creek (NABLC) and CH2MHill. Ms. Dawn Hayes represents the Naval Facilities Engineering Command and served as our principal contact to NABLC and the regulators. Without her help and intervention, this demonstration would not have been possible. Mr. Randy Sawyer and Mr. Channing Blackwell represent the Commander, Navy Mid-Atlantic Regional Command as Installation Restoration Program Coordinators. Both gentlemen were critical in realizing this demonstration by their support at the regional level. Locally, this study was supported by Ms. Stephanie McManus, NAB Little Creek Environmental Supervisor, and her office. Mr. Donn Zwirn, NABLC Public Works, and his team of electricians and plumbers prepared the field site for us and were available to fix problems when needed. Also, we thank the commander of the School of Music for permitting us access to his facilities. We acknowledge the support received from CH2MHill, especially Mr. Matt Louth, Activity Manager for Little Creek and Mr. Stacin Martin, site manager. CH2MHill provided us with logistical and technical support and gave us access to their facilities. We also thank Mr. Roy Wade, who served as our ESTCP Liaison Officer. Finally we would like to acknowledge the work of our students, Ms. Rebecca Hinrichs, Ms. Leah Wolf, Ms. Jennifer Krohn, Mr. Kevin Neary, Mr. David Blitzer, Mr. Gustavo Perez, Mrs. Laura Allen, and Mr. Craig Devine. These students were willing to work long hours under hot and humid conditions with competence and good humor. This demonstration would not have been possible without them.

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**List of Acronyms**

| | |
|---|---|
| AFB | Air Force Base |
| ARARs | Applicable or Relevant and Appropriate Requirements |
| atm | Atmospheres |
| bgs | Below Ground Surface |
| BTC | Breakthrough Curve |
| c | Means of 5 initial RFs for a compound |
| C/Co | Relative Concentration |
| CD | Cyclodextrin (specifically: hydroxypropyl-beta-cyclodextrin) |
| CDEF | Cyclodextrin Enhanced Flushing |
| CERCLA | Comprehensive Environmental Response Compensation and Liability Act |
| CMC | Critical Micelle Concentration |
| CFR | Code of Federal Regulations |
| CMCD | Carboxymethyl-ß-cyclodextrin |
| Co-PI | Co Principal Investigator |
| CPPT | Cyclodextrin Push-Pull Test |
| CSM | Colorado School of Mines |
| DERP | Defense Environmental Restoration Program |
| DNAPL | Dense Non-Aqueous Phase Liquid |
| DO | Dissolved Oxygen |
| DoD | Department of Defense |
| EC | Electrical Conductivity |
| *E 1* through *E 7* | Extraction Wells |
| EPA | Environmental Protection Agency |
| ESTCP | Environmental Security Technology Certification Program |
| FS | Feasibility Study |
| gpd | gallons per day |
| gpm | gallons per minute |
| GW | Ground water |
| HASP | Health and Safety Plan |
| He | Helium |
| HPCD | Hydroxypropyl-ß-cyclodextrin |
| HRSD | Hampton Road Sanitation District |
| *I 1* | Injection Well |
| IAS | Initial Assessment Study |
| I/E | Injection/Extraction Test (a.k.a. line-drive test) |
| IPA | Isopropyl Alcohol |
| IRI | Interim Remedial Investigation |
| ISE | Ion Selective Electrode |
| K | Hydraulic Conductivity |
| $K_{NW}$ | NAPL-water portioning coefficients |
| LANTDIV | Atlantic Division, Naval Facilities Engineering Command |
| lpm | liters per minute |
| MCL | Maximum Contaminant Level |

| | |
|---|---|
| MDL | Method Detection Level |
| MIP | Membrane Interface Probe |
| MSDS | Materials Safety Data Sheet |
| MW | Monitoring Well or Molecular Weight |
| n | Number of measurement or calibration points (x,y data pairs) |
| Ne | Neon |
| NABLC | Naval Amphibious Base Little Creek |
| NACIP | Navy Assessment and Control of Installation Pollutants |
| NAPL | Non-Aqueous Phase Liquid |
| NRC | National Research Council |
| NTR: | Navy Technical Representative |
| OVM | Organic Vapor Meter |
| OSHA | Occupational Health and Safety Administration |
| PAH | Polycyclic Aromatic ydrocarbon |
| PAT | Pump-and-Treat |
| PCE | Tetrachloroethylene (tetrachloroethene) |
| PI | Principal Investigator |
| PID | Photoinonization Detector |
| POTW | Publicly-Owned Treatment Works |
| ppb | Parts per Billion (approximately 1 ug/L) |
| ppm | Parts per Million (approximately 1 mg/L) |
| PTT | Partition Tracer Test |
| Pre-PTT | Partition Tracer Test conducted before CDEF demonstration |
| Post-PTT | Partition Tracer Test conducted after CDEF demonstration |
| PWC | Public Works Center |
| QA | Quality Assurance |
| QAPP | Quality Assurance Project Plan |
| QA/QC | Quality Assurance/Quality Control |
| QC | Quality Control |
| RCRA | Resource Conservation and Recovery Act |
| RF | Fluorescence Spectrophotometer |
| $RF_1$ | Average relative response factor from initial calibration |
| $RF_2$ | Response factor from continuing calibration. |
| RPD | Relative Percent Difference |
| RSD | Relative standard deviation |
| RVS | Round 1 Verification Step |
| SARA | Superfund Amendments and Reauthorization Act |
| SD | Standard deviation |
| SIC | Standard Industrial Classification |
| $S_N$ | NAPL saturation |
| SOP | Standard Operation Procedure |
| SWDA | Solid Waste Disposal Act |
| T | Temperature |
| TCD | Thermal Conductivity Detector ( |
| TCE | Trichloroethylene (trichloroethene) |
| TDP | Number of total samples obtained |

| | |
|---|---|
| TNS | 6-(p-Toluidino)-2-naphthalenesulfonic acid, sodium salt |
| TNT | 2,4,6-trinitrotoluene |
| UF | Ultrafiltration |
| UHP | Ultra-high purity |
| UA | University of Arizona |
| URI | University of Rhode Island |
| UTSA | University of Texas, San Antonio |
| VADEQ | Virginia Department of Environmental Quality |
| VDP | Valid Data Points |
| VOC | Volatile Organic Compound |
| x | Calibration concentrations |
| y | Instrument response (peak area) |

| | |
|---|---|
| 1,1-DCA | 1,1-dichloroethane |
| 1,1-DCE | 1,1-dichlorethene |
| 1,2-DCE | 1,2-dichloroethene |
| 1,1,1-TCA | 1,1,1-trichloroethane |
| 2EH | 2-ethyl-1-hexanol |
| 22DMP | 2,2-dimethyl-3-pentanol |
| 22DMPP | 2,2-dimethyl-1-propanol |
| 23DMB | 2,3-dimethyl-1-butanol |
| 26DMHP | 2,6-dimethyl-4-heptanol |
| 44DMP | 4,4dimethyl-2-pentanol |
| 6MH | 6-methyl-2-heptanol |

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# 1. Introduction

## 1.1. Background Information

Chlorinated organic compounds and complex mixtures of these compounds have been identified as a common cause of groundwater contamination at many sites. When these contaminants are present as a separate phase, they are commonly referred to as a non-aqueous phase liquid (NAPL). NAPL spills in the subsurface are considered the single most important factor limiting remediation of organic-contaminated sites (NRC, 1994). Whenever NAPL is located below the water table, it serves as a long-term source for groundwater contamination. Non-uniform flow patterns, dilution effects, and non-homogeneously distributed NAPLs in concert with limited mass transfer between the organic and aqueous phases can severely constrain the effectiveness of conventional remediation systems. As a result, very long times (e.g. decades) may be required to remove the contamination (e.g. Schwille, 1975; Mackay et al., 1985; Powers et al.; 1991; Mayer and Miller, 1996; McCray et al., 1999). Consequently, water-flushing techniques (i.e. conventional pump-and-treat methodologies), remove contaminant mass too slowly (e.g. Mackay et al., 1985; Mackay and Cherry, 1989), and excavation is generally not practical because of the depths to which the contamination has migrated. Nevertheless, about 93% of all groundwater remediations conducted on CERCLA sites use conventional pump-and-treat schemes (NRC, 1994; Begley, 1997). The generally limited performance of conventional groundwater pump-and-treat systems has led to consideration of innovative chemically enhanced-flushing methods.

Chemically enhanced-flushing technologies are based on flushing the contaminated porous medium with chemical agents to increase contaminant solubility. Concomitantly the mass removal rate is elevated, which reduces the time and cost of remediation. Chemically enhanced-flushing technologies are particularly useful for the treatment of DNAPL source zones. Chemical treatment of contaminated zones often becomes attractive where (1) alternative methods (e.g. bioremediation) are incompatible or will not function effectively with respect to rate or extent of treatment (Yin and Allen, 1999), (2) localized, highly contaminated zones in heterogeneous systems, or (3) where the access to the contaminated soil and groundwater is difficult due to restricting surface structures or uses. The selection of a particular chemical in-situ treatment technology depends on various factors, with the most important factors typically being: (1) the site-specific hydrologic and geologic conditions, (2) the contaminant inventory, and (3) the cost and environmental safety of the treatment method. This project focuses on a particular class of chemical flushing agents called cyclodextrins. Cyclodextrins are non-toxic, modified sugars. The particular cyclodextrin being used for this project is called hydroxypropyl-**ß**-cyclodextrin (HPCD). If not stated otherwise, the term "cyclodextrin" in this report refers to HPCD.

Cyclodextrin-enhanced in-situ flushing (CDEF) of contaminated porous media generally begins with the injection of a water-based cyclodextrin solution. This solution is flushed through the contaminated aquifer and then extracted. Conventional injection and extraction wells can be used to control the flowfield of the flushing solution. This application scheme is in principle similar to conventional pump-and-treat systems, but due to the advantageous solubility enhancing properties of the cyclodextrin solution, mass removal rates are faster and consequently remediation times should be shorter. Because the magnitude of solubilization of organic contaminants is a linear function of the aqueous cyclodextrin concentration, the contaminant removal rate can be raised by increasing the cyclodextrin concentration. The extracted flushing solution containing the contaminant-cyclodextrin complex is treated by air stripping. Air stripping separates the volatile contaminants from the cyclodextrin solution. Before re-injection into the contaminated aquifer, the flushing solution's cyclodextrin content is re-concentrated using a membrane filter that separates the cyclodextrin from the aqueous phase. This recycling of the flushing agent limits the material needs and increases the cost-effectiveness of the technology.

### 1.2 Regulatory Drivers and Stakeholder/End-User Issues

The primary Federal legislation dealing with hazardous waste disposal was RCRA, passed in 1976. RCRA dealt only with current and future hazardous waste management and disposal practices until it was amended in 1984 by the Solid Waste Disposal Act (SWDA). In 1981, the Department of the Navy initiated a program to investigate past disposal sites at military installations. The program, the Navy Assessment and Control of Installation Pollutants (NACIP), called for a three-phase operation. Phase One was the Initial Assessment Study (IAS), which basically consisted of a literature and record search to identify potentially contaminated areas. Phase Two was the Confirmation Study, which typically was a two-step investigation process consisting of a Round 1 Verification Step (RVS) to verify and/or characterize the contamination followed by a more detailed investigation if necessary to define the extent of contamination. Phase Three included the Remedial Action. The NACIP program was changed in 1986 to reflect the requirements of the Comprehensive Environmental Response Compensation and Liability Act (CERCLA) as amended by the Superfund Amendments and Reauthorization Act (SARA). Part of CERCLA/SARA is a Feasibility Study (FS) to evaluate the potential remedial alternatives. The final step is the implementation of the selected remedial alternative.

The Defense Environmental Restoration Program (DERP) provides for the identification, investigation, and cleanup of hazardous waste sites at Department of Defense (DoD) facilities. DERP focuses on cleanup of contamination associated with past DoD activities to ensure threats to public health and the environment are eliminated. Section 2701 states as a goal “the identification, investigation, research and development, and cleanup of contamination from hazardous substances, pollutants, and contaminants.“ SARA Section 211, which established DERP, also provided for:

- Means of reducing the quantities of hazardous waste generated.

- Methods of treatment, disposal, and management (including recycling and detoxifying) of hazardous waste.

- Cost-effective technologies for cleanup of hazardous substances.

- Toxicological data collection and methodology on risk of exposure to hazardous waste.

- Testing, evaluation, and field demonstration of innovative methods to control, contain, and treat hazardous substances.

DoD's Office of Environmental Cleanup is charged with developing policy and overseeing the DERP. All activities shall be carried out subject to, and in a manner consistent with, section 120 (relating to Federal facilities) of the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 and in consultation with the Administrator of the Environmental Protection Agency.

In a report of the Institute for Defense Analyses (O'Brien, 2001), the primary goal in most industrial remediation projects is to achieve an environmentally acceptable, expedited cleanup of a site at a fixed price. Other related objectives include:

- Limiting exposure to risks associated with environmental cleanup
- Predictable budgeting and cash flow management
- Obtaining financial assurance and insurance to secure contractor performance to adequately protect its, and the buyer's, interests
- Improving productivity by redirecting resources to core business activities
- Accelerating the transfer of distressed real estate assets
- Maintaining adequate level of management control
- Obtaining enhanced tax position

The CDEF technology addresses these regulatory requirements and stakeholder issues. By quickly and cost-effectively removing DNAPL from the subsurface, CDEF prevents further migration of the DNAPL and mitigates a continuing source of contamination to the dissolved-phase plume. Consequently, the volume and exposure of hazardous waste is reduced and site closure can be accomplished sooner. A cost/performance assessment, which is part of this final report, provides end-users with solid data for sound business decisions.

Although CDEF has great advantages compared to other existing remediation technologies, there are sites where this approach may not be appropriate or must be used in combination with other technologies. For example, CDEF technology has been primarily used for the removal of residual NAPL. If free-moving NAPL is encountered inside a well other technologies, such as free-product skimming, should be applied prior to CDEF. Also, CDEF should not be expected to bring down contaminant concentration to below drinking water limits. However, CDEF technology may lower the contaminant concentration enough to permit the application of otherwise impossible remediation approaches, e.g. enhanced bioremediation.

### 1.3 Objectives of the Demonstration

The CDEF technology demonstration was intended to show the potential of cyclodextrin technology under full-scale operational conditions. The particular objectives of this demonstration were (1) evaluation of the cost and performance of cyclodextrin enhanced removal of dense nonaqueous phase liquids, DNAPLs, from polluted groundwater, (2) testing unrefined, liquid CD as substitute for CD powder, (3) evaluate membrane technology for recovering and reusing CD, (4) identifying most appropriate wastewater treatment technology(-ies), and (5) conducting PTT for mass balancing.

The demonstration was conducted to remove a chlorinated hydrocarbon DNAPL present in the subsurface adjacent to a former plating-shop once operated by the Naval Amphibious Base Little Creek (NABLC), School of Music, in Virginia Beach, Virginia ("Site 11"). The principal contaminants were TCE and 1,1,1-trichloroethane (1,1,1-TCA). These chlorinated solvents were used for degreasing metal surfaces of musical instruments prior to plating. DNAPL has entered the subsurface through a leaking (since removed) neutralization tank and contaminated soil and groundwater. This scenario is very typical for many contaminated military and industrial sites. The medium that was treated was a predominantly sandy, unconfined aquifer with a shallow water table. Before cyclodextrin flushing, a partition tracer test (PTT) was conducted to establish pre-demonstration contamination levels. A second PTT was conducted after the demonstration. The second PTT compared to the first PTT together with mass balance computations based on the VOC content of the extracted flushing solution served as a measure for the removal effectiveness of the CD technology.

In addition to the subsurface treatment by CDEF, this project was also designed to demonstrate aboveground treatment alternatives for the extracted contaminant-cyclodextrin solution. For this purpose, a membrane filtration system was evaluated. The system consisted of an ultrafiltration (UF) unit that allowed for the passage of water, but retained the CD. By passing the CD solution extracted from the subsurface through the UF, the CD solution was reconcentrated. The reconcentrated CD solution was then reinjected into the subsurface. The membrane system also consisted of a pervaporation (PVP) unit. The PVP unit removed volatile contaminants, such as TCE, from the recovered CD flushing solution by using a thermally enhanced membrane separation process. The treated CD solution leaving the PVP was either reinjected or sent to the UF for CD reconcentration. The volatile contaminants that passed through the PVP membrane were concentrated in the PVP effluent. Alternatively to the PVP, a standard air-stripper was used to remove the volatile contaminants from the extracted CD solution. The efficiency and performance of the air-stripper unit was compared to that of the PVP. Cost-effective contaminant removal and CD reconcentration techniques are considered the corner stones of the CDEF technology. This demonstration provides the data necessary to evaluate the various treatment alternatives.

Funded by the Environmental Security Technology Certification Program (ESTCP), this project was intended as a technology demonstration only – the remediation of the entire test site was not an objective. The overall duration of the demonstration was 4 months

(June through September 2002). During this period, approximately 32.5 kg TCE and 1,1,1-TCA were removed plus and estimated 2.9 kg 1,1-DCE No active remediation system has been installed at the test site before or after this demonstration. Thus, the performance of CDEF was compared to the effectiveness of a conventional pump-and-treat system. This technology comparison was based on chemical data obtained during the PTTs (i.e. before and after CDEF application). This approach is reasonable because a PTT closely resembles a pump-and-treat water flushing system. During the pre- and post-PTT, the average concentration of TCE and 1,1,1-TCA were 23.7 mg/L and 10.2 mg/L, respectively. During the CD flood, the contaminant concentrations increased to up to 270 mg/L TCE and 491 mg/L 1,1,1-TCA. Compared to pump-and-treat, the maximum solubility enhancement during CDEF was more than eleven times higher for TCE and 48 times higher for 1,1,1-TCA. Based on the PTTs results and mass balance calculations, the DNAPL saturation decreased by approximately 81% after the CDEF demonstration. Although many unexpected problems were encountered, e.g. less than expected treatment capacity of the membrane system, these numbers clearly demonstrate that CDEF technology increased the rate of DNAPL removal relative to conventional water flooding.

### 1.4 Previous Testing of the Technology

Cyclodextrins were first used for pharmaceutical purposes and in the food processing industry. The use of cyclodextrins as an agent for chemically enhanced in-situ flushing was introduced by Brusseau and colleagues (Wang and Brusseau, 1993; Brusseau et al., 1994; Brusseau et al., 1997a). In recent years, several laboratory studies have been performed on cyclodextrin and its potential use for remedial application. For example, McCray et al., 2000, measured and tabulated cyclodextrin-enhanced solubilization for a suite of typical organic groundwater contaminants (in a 10% w/w cyclodextrin solution). These researchers found that more hydrophobic compounds experience a larger relative solubility enhancement than more hydrophilic contaminants. For example, the enhancement factor for (more hydrophobic) DDT is increased 1100 fold in the presence of 10% HCPD, while (more hydrophilic) naphthalene showed a smaller, 53 fold increase. It is noteworthy that the total mass of contaminant that can be solubilized by cyclodextrin solution is greater for naphthalene than for DDT. This occurs because the overall enhanced solubility (water solubility times the enhancement factor) is generally greater for the more soluble compounds. Boving et al., 1999b, using a laboratory scale air stripper, demonstrated that it is possible to separate volatile organic contaminants, such as TCE, PCE, or toluene, from a HPCD solution without affecting its solubility enhancing performance. In contrast to most surfactants (e.g. SDS), foaming of the cyclodextrin solution during air stripping was negligible. Finally, cornstarch, from which cyclodextrins are derived from, does not have solubilization enhancing properties (Boving et al., 2001).

Prior to the ESTCP funded CDEF demonstration, selected aspects of the cyclodextrin technology had already been studied under pilot-scale field conditions. The mass removal effectiveness of a 10.4% w/w HPCD solution for flushing fuel-based NAPL chemicals (aliphatic, aromatic, and chlorinated hydrocarbons) was examined in a pilot test conducted at Hill AFB in Utah (McCray and Brusseau, 1998, McCray and Brusseau, 1999; Brusseau et al., 1999a). These authors report that the aqueous concentrations of twelve target compounds (including TCE, TCA, BTEX, trimethylbenzene, 1,2-dichlorobenzene, and several alkanes), as measured in extraction wells during the 8 pore volume (10-day) cyclodextrin flush, were about 100 to more than 20,000 times greater than the extraction-well concentrations measured during a water flush conducted immediately prior to the cyclodextrin flush. They also found that the HPCD solution allowed nearly equilibrium dissolution of contaminant, while the water flush conducted prior to the HPCD flush showed significant rate-limited mass-transfer processes as evidenced by tailing of the effluent concentrations. Blanford et al., 2000 investigated air stripping of TCE from HPCD solution under field conditions as part of a vertical circulation study conducted in Arizona. By using a commercially available air stripper, these authors successfully decreased TCE concentration from 900 ppb in a 7% HPCD solution to below detection levels (0.3 ppb). This ability enabled regulatory compliance for the reuse of the HPCD solution. Furthermore, the removal rate was fast, uniform, and complete, allowing the immediate re-injection of the treated flushing solution. However, all the previous field tests were not conducted under full-scale operating conditions and without focus on the cost-effectiveness of the technology. Conversely, the project described in this report was conducted under environmental conditions that are commonly encountered at many other DNAPL contaminated sites. And, for the first time, this project provides a complete data set that permits direct (performance and budgetary) comparison with other treatment alternatives.

# 2. Technology Description

## 2.1 Introduction

The CDEF technology was demonstrated at NABLC from June to September 2002. The demonstration included recovery and recycling of CD solution for reinjection into the DNAPL-contaminated subsurface at Site 11 (School of Music). The project was carried out as a joint effort by the University of Rhode Island, Kingston (project leader), the Colorado School of Mines, Golden, the University of Arizona, Tucson, and the Louisiana State University, Baton Rouge. Additional in-kind support was provided by the Naval Facilities Engineering Command, Atlantic Division (LANTDIV) and CH2MHill, Virginia Beach office. This report summarizes the field operations and technical performance of the CDEF technology demonstration that was conducted at NABLC.

## 2.2 Technology Development and Application

Cyclodextrins are non-toxic sugars and produced domestically at commercial quantities from corn-starch. The cyclodextrin molecule forms complexes with organic contaminants and, in some cases, with metals. For most non-polar contaminants, residence in the hydrophobic interior of the cyclodextrin molecule (Figure 2.1) is more attractive than being dissolved in water. The formation of cyclodextrin-contaminant complexes significantly increases the apparent solubility of many low-solubility organic contaminants and is the basis for cyclodextrin use in groundwater remediation. Therefore, the solubility enhancement of low polarity organic compounds by cyclodextrin is analogous to that of certain surfactants and alcohols. However, many of the disadvantages associated with surfactants and alcohols (NAPL mobilization, sorption of surfactants to soils, toxicity of the chemical reagents, and difficulty in separating the agents from the contaminants in the waste stream) are not applicable to cyclodextrin-enhanced remediation.

The fluid properties of CD solution (i.e. density, viscosity) are similar to that of water (e.g. Boving et al., 1999b; McCray et al., 2000). Also, CD is stable under typical environmental conditions. However, given the glucose-based composition of cyclodextrin, traces of cyclodextrin that may remain in the subsurface after remediation are expected to biodegrade eventually (McCray et al., 2000). CD does not precipitate nor is it affected by the pH as are many surfactants. Cyclodextrin is non-reactive, i.e. it does not adsorb to the aquifer materials and its transport through the aquifer is not retarded. As Boving et al. (2001) demonstrated, CD does not adsorb to activate carbon. The addition of cyclodextrin to the flushing solution lowers the interfacial tension between the organic phase and water, but not to a degree where mobilization of DNAPL becomes an issue. This is an important finding, because mobilized DNAPL is difficult to control during pumping operations (c.f. Fountain, 1997) and is therefore often considered to be disadvantageous during groundwater remediation.

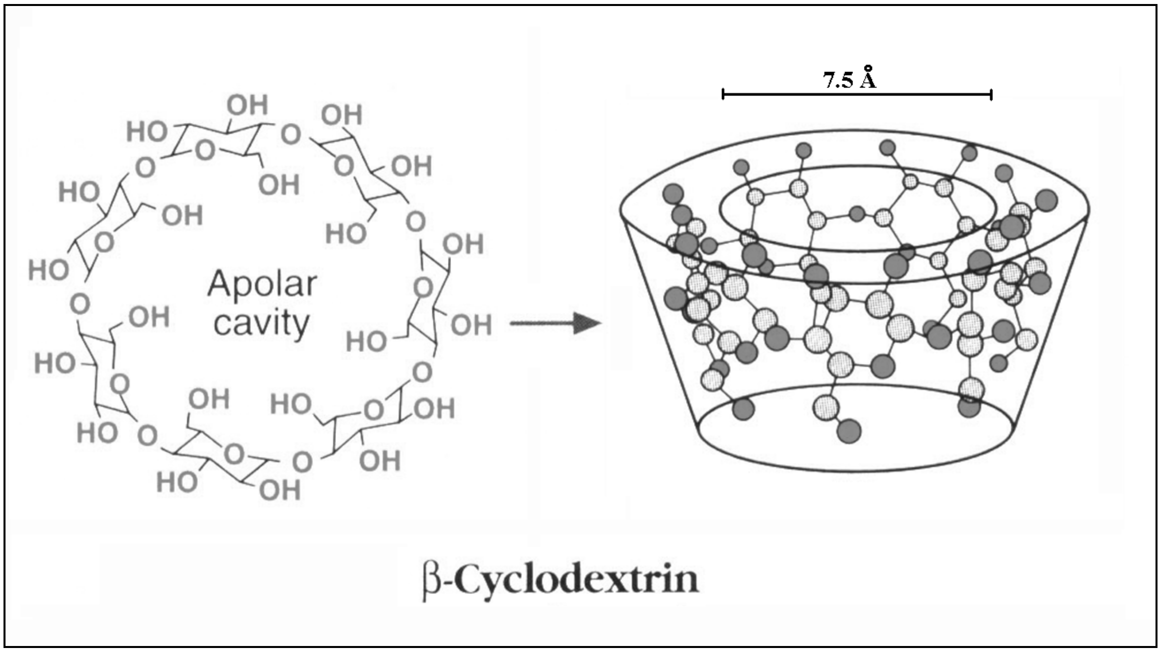



**Figure 2.1:** Two-dimensional and three-dimensional structure of the ß-cyclodextrin molecule. The interior of the molecule is hydrophobic and forms a complex with TCE. The exterior is hydrophilic and allows for a high water solubility of the cyclodextrin molecule (after Boving and McCray, 2000).

Prior to a CDEF application, the DNAPL treatment zone must be carefully characterized. The treatment zone characterization must include – at least - investigation of the geologic and hydrologic site conditions, the site history, and the delineation of the DNAPL contaminated zone ("sweep pore volume"). A properly conducted site characterization provides the basis for a cost-effective design of CDEF technology. In addition, numerical simulation of the hydraulic conditions at the site and simulation of potential contaminant fate and transport issues are essential to optimize the CDEF design. A properly designed CD injection and extraction system permits control (1) of the flow of CD solution through the DNAPL zone and (2) capture of the CD solution at the extraction well(-s). Optimal control and capture of the flushing solution translates directly in time and cost-savings during CDEF operation. The anticipated treatment volume and contaminant concentration also dictate the design of the aboveground treatment train, e.g. size and construction of the air stripper or PVP or the capacity of the UF system. The key design parameters for CDEF are listed in Table 2.1.

Each site requires careful evaluation of all parameters listed in Table 2.1. Some site that exhibit unusually complex hydrogeologic conditions or otherwise unfavorable conditions (such as limited accessibility) may require additional considerations or may not be appropriate for CDEF at all. Similarly, the CDEF performance also varies from site to site. The main performance parameters are (after NFESC, 2001):

- Final average DNAPL saturation (i.e., the volume percent of the pore space that contains DNAPL after treatment)
- The percent of initial contaminant mass removed (for example, 99%)
- The percent mass recovery of the injected CD

**Table 2.1. Key Design Parameter for CDEF**

| Design Parameter | Key Design Questions |
|---|---|
| Source zone characterization | • Is there evidence for NAPL?<br>• If so, how much NAPL is present and where is it residing (i.e. volume and extent of contamination)?<br>• What is the hydraulic conductivity and thickness of the source zone and is it sufficiently large to permit CDEF?<br>• If the aquifer is sandwiched between other geologic strata, what are their permeabilities and hydraulic characteristics and how do they compare to the source zone aquifer? |
| Numerical Simulation | • Which is the appropriate number and constellation of the well field to accomplish (1) hydraulic containment and (2) optimal capture of the CD flushing solution?<br>• What is the (potential) influence of subsurface heterogeneities (such as hydraulic conductivity variations or stratification) on the CD delivery to the DNAPL source zone?<br>• How much mass of CD must be applied to reach the clean-up target? How many sweep volumes does this amount of CD mass translate into? |
| Treatment train | • What is the most appropriate treatment method for the contaminated groundwater (PVP or air-stripping)? Which regulatory requirements apply?<br>• What is the most economic pump-rate relative to the cost and size of the treatment equipment?<br>• Is recovering the CD with a UF system more economic compared to replacing spent CD with fresh product? |

In addition to these performance parameters, the risk associated with any DNAPL remaining after treatment in combination with the risk reduction accomplished by the DNAPL removal action has to be considered. The quantification of these risks is again site specific and depends on various variables, such as future use of the site, proximity to the next drinking water supply wells and regulatory requirements. In general, quantification of the risk of the DNAPL remaining in the subsurface after CDEF is more important than quantification of the risk reduction associated to DNAPL removal during CDEF. For this demonstration, PTTs were conducted to estimate the amount of DNAPL remaining in the subsurface after CDEF.

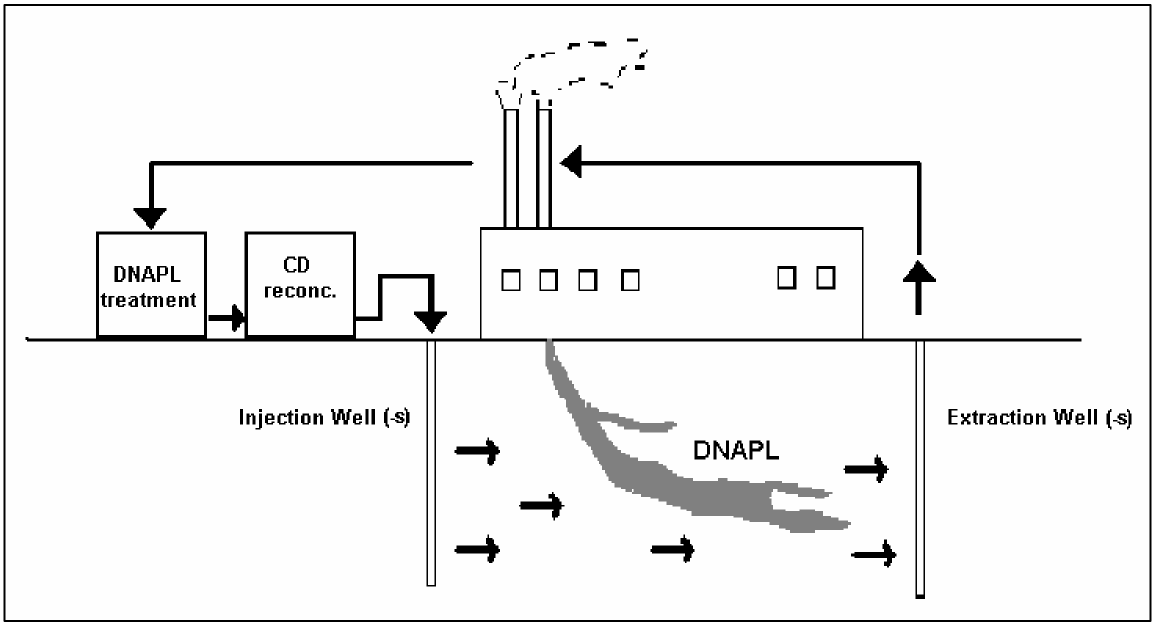



**Figure 2.2:** Conceptual illustration of the CDEF

Figure 2.2 shows a conceptual illustration of the CDEF. For this demonstration project, CD flushing solution was prepared from a 40% (wt/wt) CD stock solution (technical grade). The CD solution was delivered to the site by a tanker truck. The solution was stored in a 6,500 gal tank (Figure 2.2.) from which it was gravity feed into 4" PVC injection wells. The wells were screened over the lower-most 5 f of the Columbia aquifer, which enveloped the DNAPL source zone. As the injected CD solution moved through the DNAPL-contaminated aquifer, it complexed the contaminant and transported it to the 4" PVC extraction well(-s). The solution containing the cyclodextrin-contaminant complex was pumped to the surface and passed through a 2 µm sand filter to remove any suspended fines. Then, the solution was passed through the air stripper or, alternatively, through the PVP. VOC vapors leaving the air stripper were removed by passing through activated carbon filters. The aqueous VOC concentrate leaving the PVP was collected in a 250 gal storage tank. The VOC removal efficiency was largely controlled by the solution's residence time in the air stripper or PVP. To sustain the required residence times, the contaminated solution was (a) re-circulated until the desired clean-up level was reached or (b) a lower feed rate was maintained.

After passage through the air stripper or PVP, the treated CD solution was either processed in the UF or reinjected into the subsurface or stored in a 6,500 gal until later reinjection. The permeate (= CD depleted solution) leaving the UF was discharged into a nearby storm drain after passing discharge standards (= MCL). Before reinjection the flushing solution was reconditioned with CD stock solution to maintain the desired CD concentration of the flushing solution (20% by weight). A number of sampling ports along the process line guaranteed control over the entire treatment train.

## 2.3 Factors Affecting Cost and Performance

CDEF inherits the limitations of other conventional and innovative remediation approaches that relay on the injection and extraction of liquids from the subsurface (e.g. pump-and-treat, surfactant or cosolvent flushing). For example, the source zone containing the NAPL must have a sufficiently high permeability (in terms of hydraulic conductivity (K) = $10^{-4}$ cm/sec) to permit adequate delivery of the flushing solution and effective capture with a minimal number of wells. Ideally, as it was the case at the NABLC demonstration site, a geologic unit of low permeability (e.g. clay) should underlay the contaminated zone. Such a low permeability zone limits vertical migration of the contaminant and flushing solution and increases the degree of hydraulic control during CDEF application. Remediation cost increases and performance decreases in less permeable material (K = $10^{-4}$ cm/sec) and at very heterogeneous sites. These more complex sites require more characterization effort and bear a higher risk in terms of remediation success.

The site selected for the ESTCP demonstration of CDEF was considered “simple”. The site was characterized by a comparable shallow water table (about 2.3 m below surface), relative homogenous strata (silty-sandy sediments having a *K* ranging from $10^{-4}$ cm/sec to approximately $10^{-3}$ cm/sec) with a thick, low-permeability unit sitting at a depth of about 7.5 m below surface. Even though a lot of effort was spent characterizing the site prior to the demonstration, significant problems delivering and capturing the flushing solution were encountered. For example, the top of the underlying low-permeability unit exhibited a distinct morphology, i.e. a small trough was crossing the source zone from NE to SW. The existence of this trough was not known when the well field was installed, but it had important influence on the location of the DNAPL source zone and required modifications of the well field design (see Section 4 for further details). Thus, the actual conditions encountered during remediation may deviate from the expected “simple” conditions. Unanticipated complications usually result in cost increases due to lower than anticipated performance of the remediation system.

Next to site specific limitations that affect the cost and performance of CDEF, a major cost factor is the expense of CD. As the most common and least expensive cyclodextrin offered, HPCD, is currently prized at about 4.00 to 6.00 dollars per kilogram. The CD cost is comparable to many surfactants and it is expected that the price will come down further if the remediation market is found to be viable. For this demonstration, 6 metric tons (dry weight) of CD (as 40% technical grade solution) were used. The main factors that determine the amount of CD needed are:

1. Mixing and dilution with uncontaminated groundwater
2. Incomplete capture of the injected flushing solution
3. Effectiveness of re-concentration process
4. Operational losses of flushing solution
5. Estimated versus actual amount of DNAPL in source zone
6. Number of pore volumes to be flushed through the source zone to reach remediation goal

While the influence of factors 1 through 4 can be minimized by proper design of the well field and the treatment train, factors 5 and 6 can significantly affect the cost and duration of the demonstration.

Another important cost factor is the selection of the most appropriate effluent treatment and CD recycling technology. In this demonstration, the feasibility and cost of two effluent treatment technologies (air stripping and PVP) and one CD recycling technology (UF) was examined. Which of these systems to use at a specific site depends on (a) extraction flow rates in relation to the capacity of the treatment train, (b) availability of on-site facilities capable of treating CDEF effluent, (c) cost of CD recovery versus CD replacement cost, and (d) regulatory requirements, i.e. final contaminant concentrations in the treated effluent. In addition, it must be carefully evaluated if renting or purchasing the necessary treatment equipment is the more economic option. Short term project (i.e. less than a year) generally favor the rental option, while for longer lasting projects the equipment purchase is preferable.

Finally, this demonstration was carried out under increased security measures following the events that took place on 9/11. As a result, access to this military installation was restricted during times when the base went on increased alert levels. The delays affected the demonstration's progress and had direct impact on the cost and performance of the project.

### 2.4 Advantages and Limitation of the Technology

The principal advantages of CDEF technology are the non-toxicity of the CD itself and its ability to quickly and effectively remove NAPL compared to conventional remediation methods such as pump-and-treat. Table 2.2 lists some of specific advantages of CDEF. For a complete review of laboratory research and the theory of cyclodextrin-enhanced solubilization see Wang and Brusseau, 1993, or Boving and McCray, 2000.

| Property | Advantage |
|---|---|
| Non-toxic to humans and resident microbial populations | Cyclodextrins are widely used in pharmaceuticals, food processing, and cosmetics. Thus, there are minimal health-related concerns associated with the injection of cyclodextrin into the subsurface and increases the regulatory and public acceptance for this technology. |
| Enhances solubility at all concentrations | Individual cyclodextrins molecules complex molecule(s) of contaminant so cyclodextrins do not require a minimum concentration as surfactants. |
| Flows freely through aquifers | Cyclodextrin and cyclodextrin/contaminant complexes do not adsorb or precipitate in aquifers (e.g. Brusseau et al., 1994). This is an issue of regulatory concern. |
| Optimal performance | Cyclodextrins performance is uninfluenced by changes in pH, ionic strength, and temperature. |
| Does not persist in the environment | Cyclodextrins are resistant to biological and chemical degradation over short time periods (i.e. few months, which is the expected time-scale of remediation), but will be ultimately degrade. For comparison, surfactants often persist in the environment for long times. |
| Highly soluble | Cyclodextrins solubility exceeds 800 g/L (Blanford et al., 2000). This is advantageous for field applications because relatively high initial concentrations of cyclodextrin flushing agent can be used. |
| Fluid properties do not greatly differ from water | No density-controlled problems are expected (Boving et al., 1999b, McCray et al., 2000). Therefore, flushing solution delivery systems are similar to those for traditional water flushing. |
| Moderate reduction of interfacial tension between NAPL and aqueous phase | No or little mobilization potential. HPCD promotes NAPL solubilization instead of NAPL mobilization (Boving et al., 1999a, McCray et al, 2000). Thus, control of the remediation fluid and DNAPL phase can be maintained. |
| No partitioning into NAPL | HPCD behaves as a conservative tracer, i.e. its transport through the subsurface is not retarded (McCray, 1998, Boving et al, 1999). |
| Enhanced bioremediation of organic contaminants | Cyclodextrins can be used simultaneously for bioremediation as well as for enhanced solubilization (Wang et al., 1998, Brusseau et al., 1994; Gruiz et al., 1996) |
| Volatile contaminants can be separated from cyclodextrin solution by air stripping | Cyclodextrin solution can be safely and cost-effectively reinjected into the contaminated aquifer (Boving et al., 1998 and 1999b; Blanford et al., 2000). |

**Table 2.2**: Characteristics of the cyclodextrin technology

CDEF is an alternative to surfactant and cosolvent flushing (e.g. Lowe et al., 1999). In principle, cosolvent, surfactant, and cyclodextrin enhanced flushing are essentially a modified pump-and-treat system and share the heterogeneity-induced mass-transfer limitations inherent in such systems. The performance of these enhanced flushing technologies is site specific. A primary obstacle for in-situ chemical treatment technologies generally involves delivery, distribution, and mass transfer of chemical agents in the subsurface (Yin and Allen, 1999). For example, contaminants trapped in fine-grained sediments, such as clays, are generally difficult to extract with any flushing technology. This is because the typically low permeabilities of these sediments inhibit contact with the flushing solution, which results in slow (and often diffusion controlled) removal of the contamination from these areas. Therefore, our proposed remediation technology works best in medium to coarse-grained geologic media, such as sands, but is still applicable for fine-grained sediments. This lower efficiency could be in part compensated by allowing for longer residence times of the flushing solution in the subsurface (i.e. slower injection/extraction rates).

The presence of "dead zones" (i.e. parts of the contaminated aquifer through which no flushing solution flow takes place) and preferential pathways ("hydraulic shortcuts") are also potentially limiting factors. In most cases, these shortcomings can be overcome by careful placement of the injection well screens and by intentionally changing the flow field during application of the flushing solution.

As with any chemically enhanced flushing technology, losses of CD due to incomplete capture of the flushing solution have to be considered, especially at sites where optimal hydraulic control is impossible. Also, mixing with groundwater will dilute the flushing solution. Although the CD solution can be reconcentrated, losses due to incomplete capture require adding certain amounts CD to maintain the desired removal efficiency of the flushing solution.

Potential problems are associated with up-scaling. One goal of this demonstration was to provide sufficient information for planning and budgeting larger scale operations. Table 2.3 summarizes potential risks and limitations and possible resultant impacts on the performance of the proposed remediation technology. The listed shortcomings are not necessarily associated with CDEF only, but are fairly typical risks and limitations that can affect the performance of other chemical flushing technologies as well.

| Potential risk or limitation | Potential impact on technology performance |
|---|---|
| Inhomogeneities of aquifer | Flushing solution cannot be delivered optimally to contaminated zone; preferential flow reduces contact time of flushing solution with contaminated material |
| NAPL trapped in clay layers | By-passing of flushing solution; hampering of mass transfer results in slower remediation times |
| Poor hydraulic control and incomplete capture | Losses of flushing solution; dilution of flushing solution, creation of "dead zones" |

**Table 2.3**: Potential Risks and Limitations.

Although this demonstration has focused on the removal of a chlorinated hydrocarbon DNAPL, CD has been found to enhance the solubility of many other organic contaminants, such as pesticides, polycyclic aromatic hydrocarbons (PAH), explosives (e.g. Wang and Brusseau, 1993, Sheremata and Hawari, 2000). Also, CD has been found to enhance the bioavailability of PAH and other petroleum hydrocarbons (e.g. Gruiz et al, 1996; Wang and Brusseau, 1998). Enhanced bioavailability, in return, may augment the bioremediation of these compounds. A certain cyclodextrin variety, e.g. carboxymethyl-ß-cyclodextrin, has been demonstrated to form coordination complexes with heavy metals, such as cadmium, nickel or strontium, and at the same time form inclusion complexes with organic compounds, such as phenanthrene (Wang and Brusseau, 1995b; Brusseau et al., 1997). Bizzigotti et al., 1997, suggested using CD in combination with iron for treating PCE contaminated water. In their study, they demonstrated that the CD-PCE complex could be used to deliver the PCE to an elemental iron treatment unit in which the contaminant is destroyed, but through which the CD passes unchanged. Finally, Szente et al., 1999, found that some cyclodextrin derivates have a high sorption capacity for radiogenic iodine, which could make the application of CDEF at sites contaminated with nuclear waste possible. Though, many of these possible applications require further (field)testing.

# 3. Site and Facility Description

## 3.1 Demonstration Site Selection

The criteria and requirements used for selecting the demonstration site were:

- Well-characterized DNAPL site with a relatively small source zone in a shallow sandy and/or sandy-silty aquifer.
- Saturated zone is bounded at the bottom by a relatively impervious layer (e.g., clay or silty-clay)
- Saturated zone is not more than about 7 m (21 ft) thick.
- DNAPL mixture comprised primarily of chlorinated-solvent components
- DoD site

For this ESTCP funded demonstration project, full remediation of the demonstration site was not the primary consideration because of budgetary limitations and time constraints. Demonstration costs were kept low by focusing the site search on a relatively shallow source zone bounded by an impermeable layer. These constraints were expected to limit dilution of CD solution during flushing as well as minimized well depths. Also, a well characterized, shallow source zone helped to avoid complex vertical hydraulic controls that are likely to be implemented at more complex sites. Overall, the contamination scenario at the demonstration site realistically reflects relatively small DNAPL source zones (comprised primarily of chlorinated-solvent) on other DoD sites.

After reviewing data from a number of DoD sites, NAB Little Creek Site 11 met most of the selection criteria. The principal reasons why NABLC was selected for this demonstration were:

- The site's hydrogeology and contaminant history was well-characterized and fit the requirements listed above
- Well established working relations existed with all entities involved (e.g. military liaison, contractor, state and local agencies)
- Existing infrastructure (e.g. closeness to various supply stores, existing electrical and water hook-up, shelter for analytical equipment)

## 3.2 Demonstration Site Background and History

The following summary of the demonstration site history and characteristics was in part compiled from information provided by CH2MHill, which was the lead consultant performing the Remedial Investigation on behalf of the Atlantic Division of the NAVFACENGCOM on Site 11 at the time of the technology demonstration.

NAB Little Creek, located in Virginia Beach, Virginia, provides logistic facilities and support services for local commands, organizations, home-ported ships, and other units to meet the amphibious warfare training requirements of the Armed Forces of the United States. The base is in the northwest corner of Virginia Beach and its western border abuts the city of Norfolk, Virginia. The regional location of NABLC is shown in Figure 3.1. A map of NABLC is shown in Figure 3.2. The area surrounding this 2,147-acre facility is low lying and relatively flat with several fresh water lakes. Chubb Lake, Lake Bradford, Little Creek Reservoir/Lake Smith, and Lake Whitehurst are located on, or adjacent to, the base.

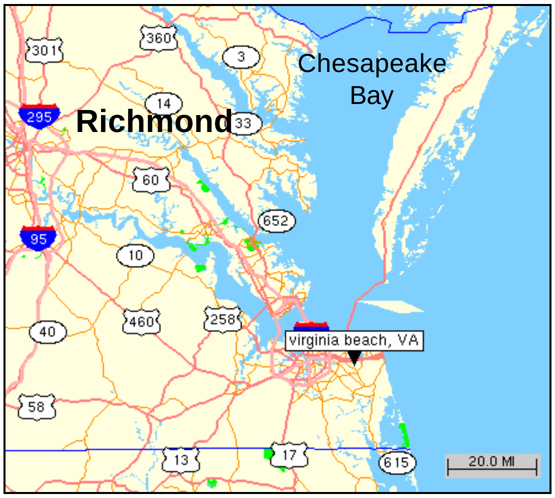



**Figure 3.1**: Regional location of NAB Little Creek in Virginia Beach, VA.


**Figure 3.2:** Naval Amphibious Base Little Creek and surrounding area.

NABLC is primarily an industrial facility that centers around three saltwater bodies: Little Creek Cove, Desert Cove, and Little Creek Channel that connects the coves with the Chesapeake Bay. In addition to industrial land-use, NAB Little Creek is also used for recreational, commercial, and residential purposes. Specifically, the southeast corner of the base had been developed for residential use. Land development surrounding the base is residential, commercial, and industrial. Little Creek Reservoir/Lake Smith, located upgradient of the base, serves as a secondary drinking water supply for parts of the city of Norfolk.

NABLC was commissioned on July 30, 1945. The Navy began purchasing land in the area from private estates and the Pennsylvania Railroad just prior to the outbreak of World War II. The first activity to be commissioned was the Amphibious Training Base in the southwestern corner of the present base near Little Creek Harbor. The base's mission was the training of landing craft personnel for operational assignments. Over the last fifty years, NAB Little Creek has expanded in both area and the complexity of its mission.

On the NABLC base, there are facilities where chlorinated solvents were used in the past (since discontinued) for various purposes, including degreasing and other cleaning activities. One of those facilities was a plating shop operated by the school of music. At that plating shop, chlorinated solvents and other industrial chemicals were discharged to a neutralization tank. Those chemicals leaked from the tank and contaminated the surficial aquifer beneath. The neutralization tank, piping, and surrounding soils were removed in 1996. The contaminated area has been designated Installation Restoration Site 11-School of Music under the Navy's Installation Restoration Program. The main contaminants listed in Table 3-1 were identified.

| **Chemical Name** | **Max Value** | **Max Location** |
|---|---|---|
| | (ug/L) | |
| **Volatile Organic Compounds** | | |
| 1,1,1-Trichloroethane | 53,000 D | LS11-GP412-11 |
| 1,1-Dichloroethane | 24,000 D | LS11-GP412-11 |
| 1,1-Dichloroethene | 11,000 D | LS11-GP412-11 |
| Chloroform | 1.000 J | LS11-GP401-07 |
| cis-1,2-Dichloroethene | 760.0 J | LS11-GP410-10 |
| Methylene chloride (Dichloromethane) | 0.400 J | LS11-GP401-07 |
| Trichloroethene | 390,000 D | LS11-GP412-11 |

**Table 3.1**: Maximum VOC concentrations in ground water at Site 11 found during hot-spot investigation, August 2001.

NABLC initiated its environmental restoration, study and investigation efforts under the NACIP Program by conducting an IAS in 1984 followed by an RVS in 1986. An Interim Remedial Investigation (IRI) was conducted by Ebasco in 1991 to determine whether further characterization activities or remedial action was warranted at Site 11. The objectives of this investigation, as identified by Naval Facilities Engineering Command, were to conduct a second round of sampling and to integrate the historical and newly acquired data along with site-specific recommendations for further action, into a single document. The data were used to develop recommended response actions, a human health assessment, and recommendations concerning additional characterization. In 1994, a Supplemental Remedial Investigation Activities (SRI) included two rounds of direct-push (geoprobe) groundwater sampling, the installation of monitoring wells and piezometers, two rounds of groundwater well sampling, the investigation of and collection of samples from sanitary sewers, and conducting water-level monitoring. The last round of investigation at Site 11 was conducted during July and August 2001, when a number of geoprobe and membrane interface probes were brought down near the former location of the disposal tank. Flute papers were used for detecting DNAPL. This investigation provided a better understanding of the site conditions then previous studies because of the vertical component of the in-situ measurement techniques used. As a result of this field investigation (together with the results of the previous SRI), the TCE source zone was narrowed down and evidence for the presence of NAPL was collected.

### 3.3 Demonstration Site Characteristics

Site 11 is located east of Building 3650, the School of Music (see Figure 3.3). The Standard Industrial Classification, SIC, code for Site 11 is *3471* (electroplating, plating, polishing, anodizing, and coloring) (after OSHA at www.osha.gov/oshstats/sicser.html). A small building (building No. 3651), the former School of Music Plating shop, is located immediately behind the School of Music (see Figure 3.3).

The School of Music Plating Shop was located in Building 3651 in the eastern area of the base, near the intersection of 7$^{th}$ and E Streets. The School of Music, located in Building 3602, is southwest of the former plating shop. The site consisted of the plating shop, an in-ground concrete tank which held plating solutions, located approximately 3 m east of the south corner of Building 3651, and its associated piping. A neutralization tank for the plating shop had a diameter of 1.5 m and the bottom of the tank was approximately 3.3 m below the land surface. In the bottom of the tank, roughly 1.9 cubic meters of crushed limestone were placed to neutralize the acidic plating bath wastes. Wastewater entered the tank through an acid-resistant drainpipe that originated in a sink in Building 3651. Neutralized wastewater was discharged from the unit by gravity into the storm sewer through an outlet and drain from the northwest side of the tank. Flow through the unit was controlled by the standpipe and outlet drain elevation so that all wastewater had to pass through the limestone before it could enter the discharge pipe connecting with the sewer. There would have to be 2.1 m of standing water in the tank before any water would flow out the outlet pipe because the top of the standpipe (the invert elevation of the outlet pipe) was approximately 2.1 m higher than the bottom of the tank.

Plating wastes were discharged into the neutralization tank during a 10-year period beginning in 1964. In 1974, the plating operations were transferred to a separate facility and discharges into the neutralization tank were discontinued. During its period of operation, the plating shop reportedly used silver cyanide, copper cyanide, chromic acid, nickel plating baths, and various acids in addition to lacquer strippers and lacquer. Small quantities of these plating baths, acids, and lacquer strippers were disposed of down the sink in the plating shop which drains into the neutralization tank and eventually into the storm sewer system. There are no existing records of chlorinated solvents such as TCE being used at Site 11, however degreasing solvents such as TCE and 1,1,1-TCA have historically been associated with similar plating shops.

*Geology:* The geologic sediments in Virginia Beach, Virginia were deposited in glacial, fluvial, and marine environments during the Holocene and Pleistocene, which later became a series of shallow sandy aquifers separated by aquitards. This shallow aquifer system at Virginia Beach, VA is composed of the Columbia aquifer, Yorktown confining unit, and the Yorktown aquifer, descending from the surface. The Columbia aquifer is composed primarily of poorly sorted sand with lenses of clay, silt, sand, peat, and shell fragments. As is the case at site 11, it is generally unconfined. It is underlain by the clay Yorktown confining unit. At Virginia Beach, the top of the Yorktown Formation, including the Yorktown confining unit and the Yorktown Aquifer, ranges from about 4.6 to 24.4 m below sea level (Smith and Harlow, 2002)

The Columbia formation consists of fine-grained sandy to silty clay beds containing shells fragments. These sediments are Holocene to Pleistocene in age. The Holocene sediments were deposited in the rivers, dunes, and shorelines since the end of the last major glacial advance approximately 11,500 years ago (Smith and Harlow, 2002). The Pleistocene sediments were deposited in similar coastal settings, primarily during marine transgressions as the continental ice sheets melted and during times when the ancient seas of the Late Pleistocene were high (Peebles et. al, 1984). The Columbia Aquifer is an unconfined aquifer; however, clayey fine sand, silt, clay, and peat deposits within the aquifer cause local confined to semi-confined conditions in some area. In other areas, sand dunes predominate and the aquifer is nearly 24 m thick (Smith and Harlow, 2002).

The Yorktown confining unit is a series of fossiliferous clay layers composing of the top of the Yorktown Formation. These clays were deposited on a shallow marine shelf in broad lagoons and bays (Meng and Harsh, 1988) during a succession of marine advances in the Early and Late Pliocene Epoch (Johnson and Berquist, 1989). Regionally, the confining unit is a series of very fine, sandy to silty clay layers of varying color. The Yorktown confining unit varies in thickness and in composition, but on a regional scale is a leaky confining unit. Some sand layers within the confining unit are capable of producing small to moderate amounts of freshwater in some areas (Smith and Harlow, 2002). The Yorktown Formation is a grey, very fine to coarse sand, in part gluconitic and phosphatic, commonly very shelly and interbedded with sandy and silty clay (Powars, 2000). The Yorktown also includes abundant microfauna and cross-bedded biofragmental lenticular sand bodies. The Yorktown aquifer is wedge shaped, thickening to the east and is generally unconfined.

Boring logs generated by CH2MHill during installation of monitoring wells at Site 11 report a layer of fine-grained materials 2.5 to 3.4 meters thick overlying a layer of sands that compose the unconfined Columbia aquifer. This fine-grained material includes clayey to sandy silt, clay, and silty sand and grades into poorly graded sand with depth through the aquifer. The thickness of the Columbia Aquifer sand appears to be approximately 4.6 m throughout Site 11 (CH2MHILL, 2001). The bottom of the Columbia Aquifer varies from 6.0 to 7.6 m below the land surface at Site 11. The Columbia Aquifer is underlain by a clay confining unit (Yorktown Confining Unit) that ranges in thickness from 9.1 to 12.2 m at Site 11 (CH2M HILL, 2001). The Yorktown Confining Unit at Site 11 consists of dense grey colored clay, silt and very fine sand. Shell and wood fragments are abundant and appears to become finer-grained and less moist to nearly dry with depth

One year prior to the CDEF demonstration, eight more boreholes were drilled at Site 11 by Parratt Wolff Inc. (Figure 3.3). The boreholes were drilled to depths between 6.1 and 7.6 m using a hollow stem auger. The inner diameter of the auger was 15.9 cm and the outer diameter was 26.7 cm. Soil samples were taken using a 5.1 cm split spoon. During collection of the soil samples, borehole logs were created to depict the construction of the well and the subsurface lithology. The wells were constructed with 10.2 cm diameter schedule 40 PVC pipe with a screen slot of V-20 slot. The wells were partially penetrating with a 1.5 m long screen interval at the bottom of the well. The wellpack was constructed with #2 sand surrounding the screened portion of the wells and bentonite was used above that to near the surface where Portland cement pad and a well fault were installed (Figure 3.4). The wells were developed by plunging with surge blocks and extracting loose sediment with a low flow pump.

For the CDEF demonstration an additional eight wells were drilled. Figure 3.4 shows the location of these wells relative to building 3651 and the location of the former UST. The data from the borehole logs (see Figure 3.5), such as the lithologic composition and structure were analyzed with groundwater modeling software (GMS version 4.0, Environmental Modeling Systems Inc., Jordan, Utah). After the bore logs are entered into GMS, 3D drawings (see Figure 3.6) and cross sections of the subsurface lithology were generated.

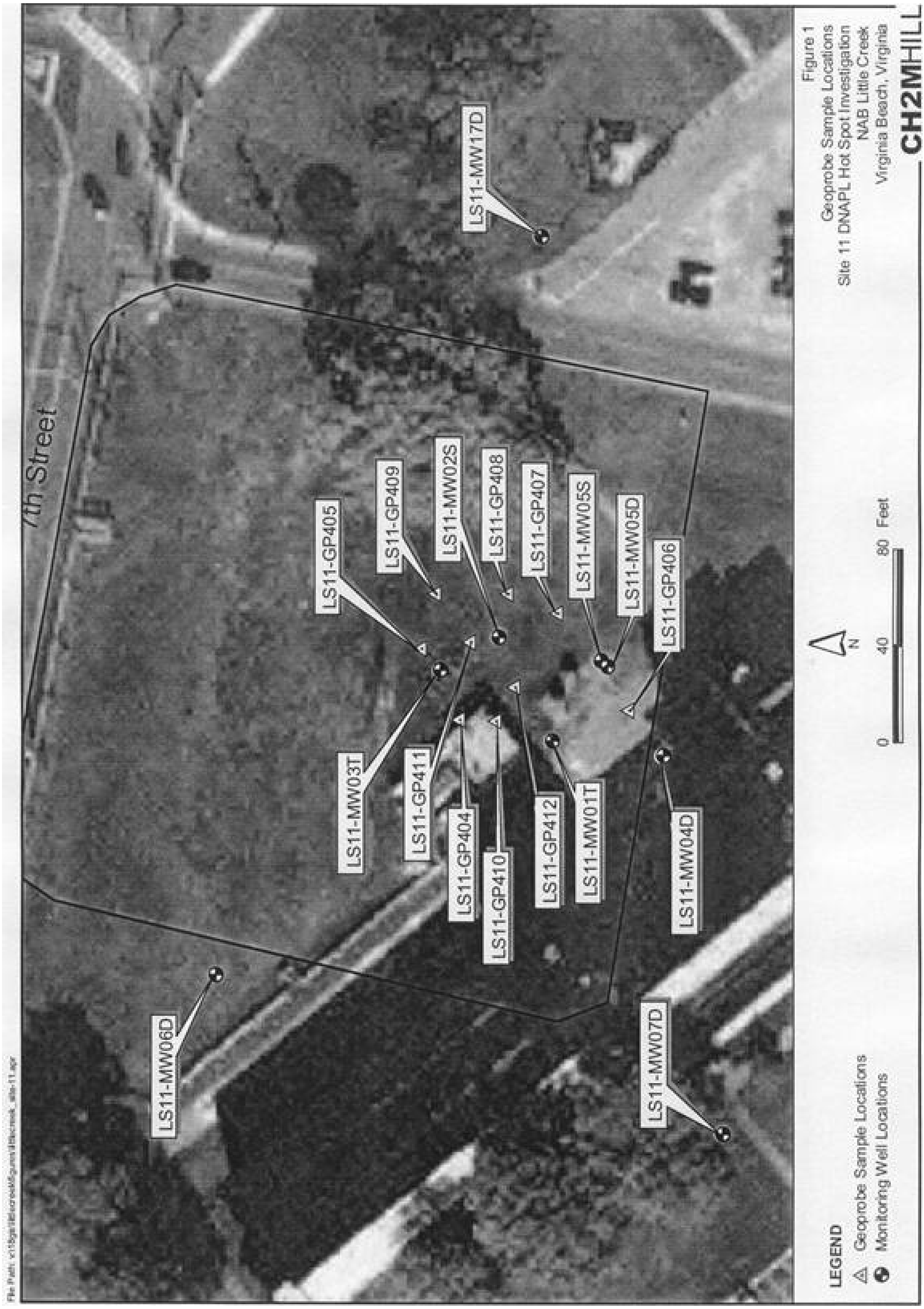



**Figure 3.3:** Location of monitoring wells (MW) and temporary Geoprobe sample locations (GP) and at Site 11 (after CH2MHill, 2001).

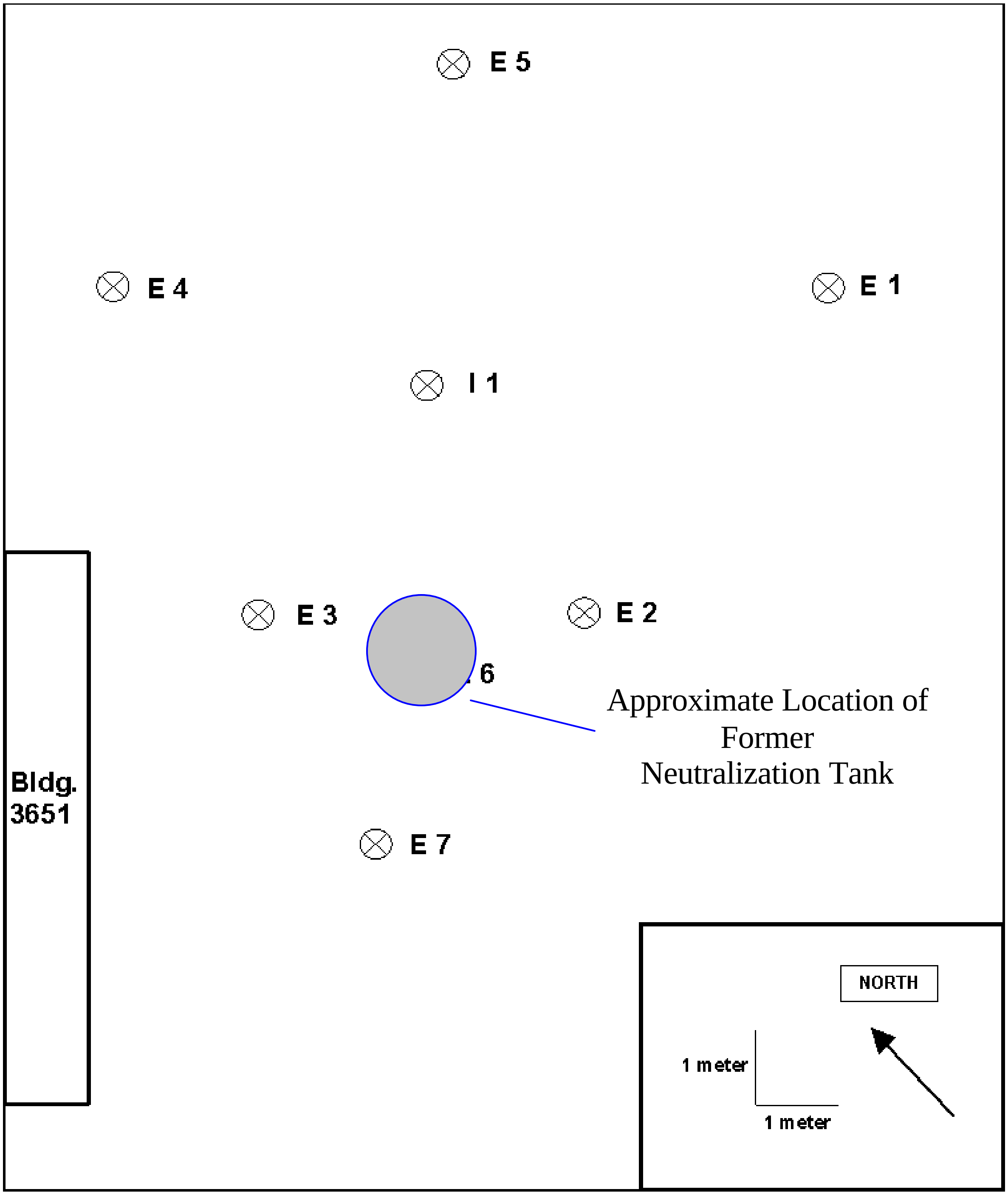



**Figure 3.4**: Location of wells drilled for the CDEF demonstration in relation to Building 3651 and the former neutralization tank.

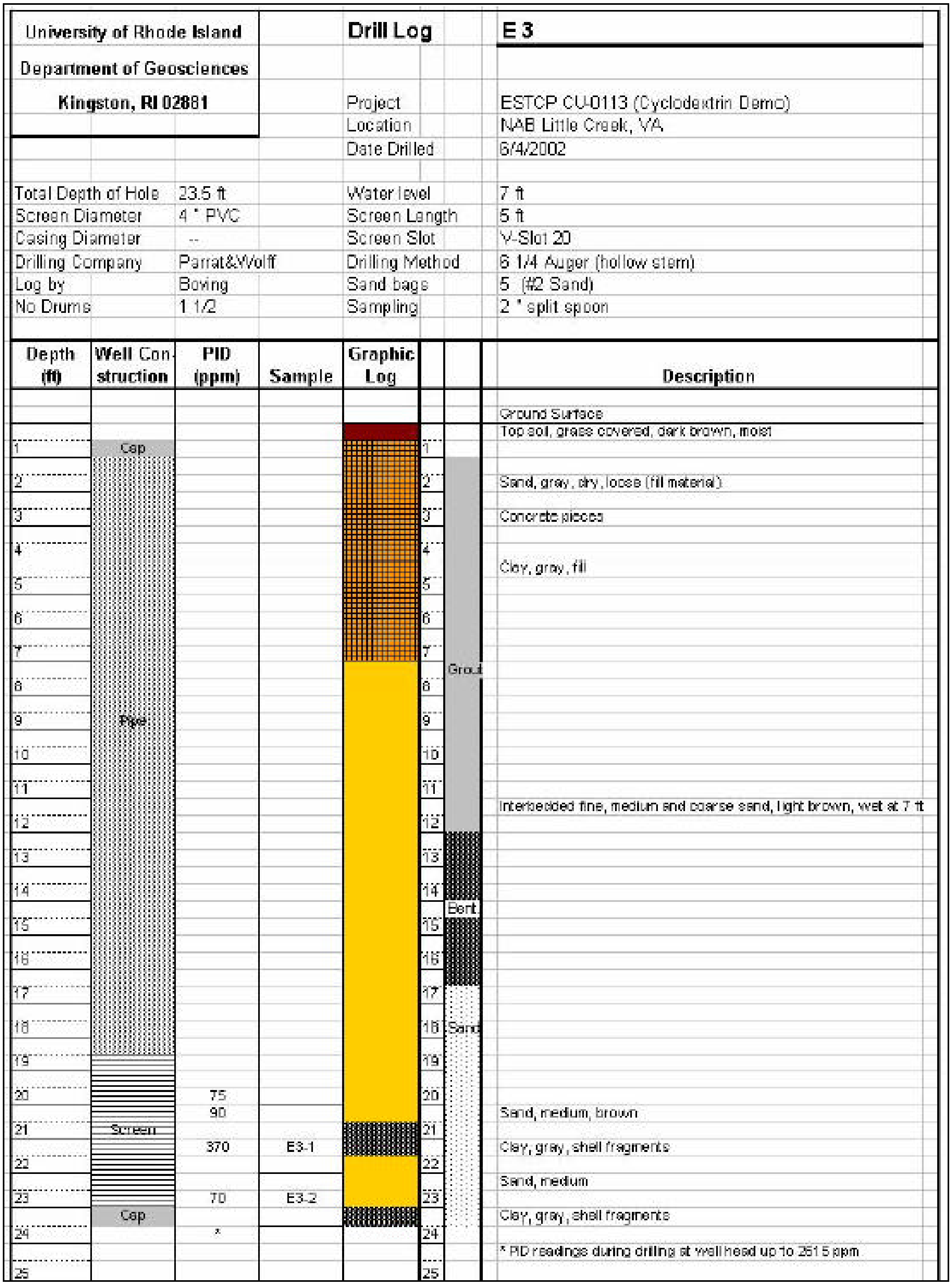



**Figure 3.5**: This is an example for one of the eight drill logs that were prepared for the CDEF demonstration (well E3). See Appendix XI for all drill logs.

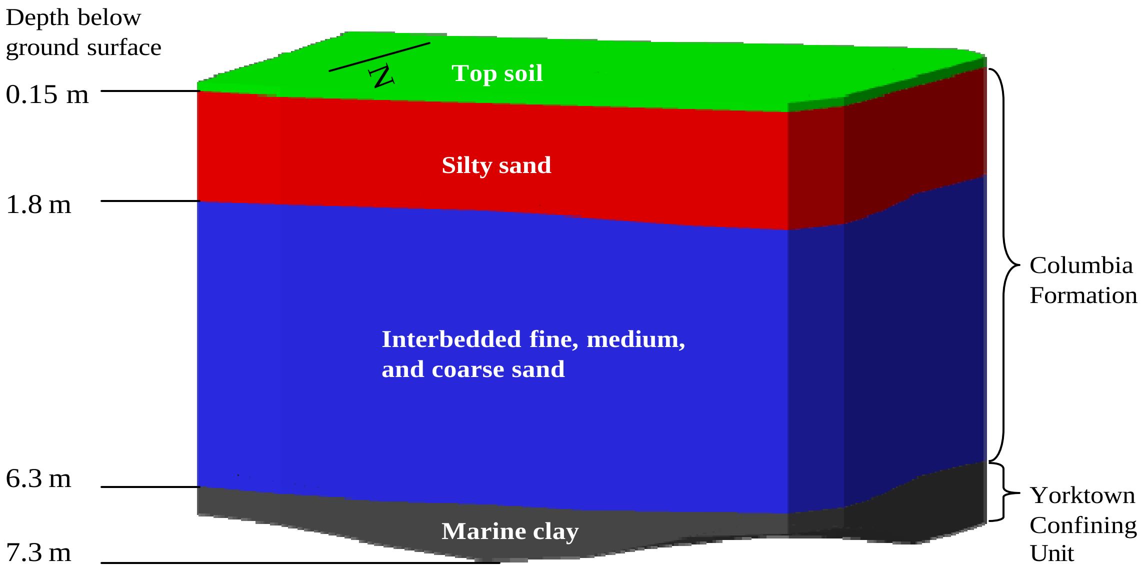



**Figure 3.6:** Simplified 3D Profile of lithologic formations at Site 11. For simplicity, clay lenses encountered at some drilling locations are not shown.

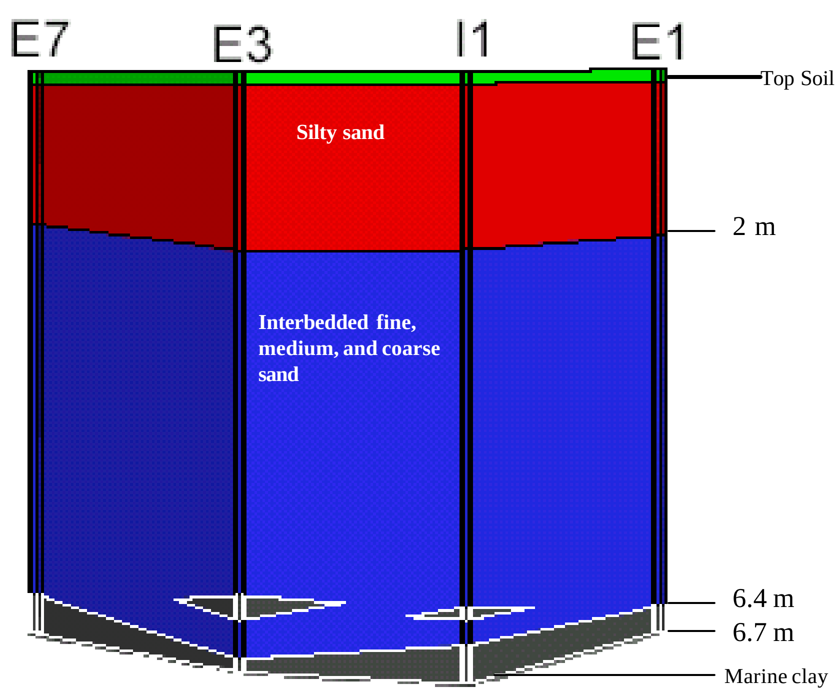



**Figure 3.7**: Cross section through Site 11 showing clay lenses at Wells E3 and I1.

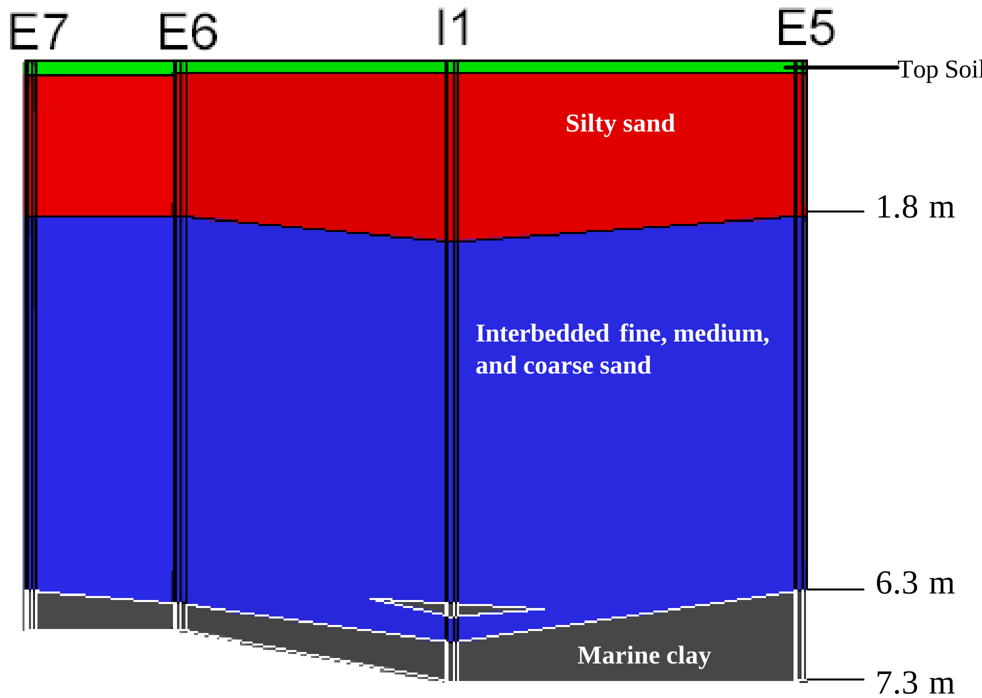



**Figure 3.8:** Cross section through Site 11 showing clay lens at Well I1.

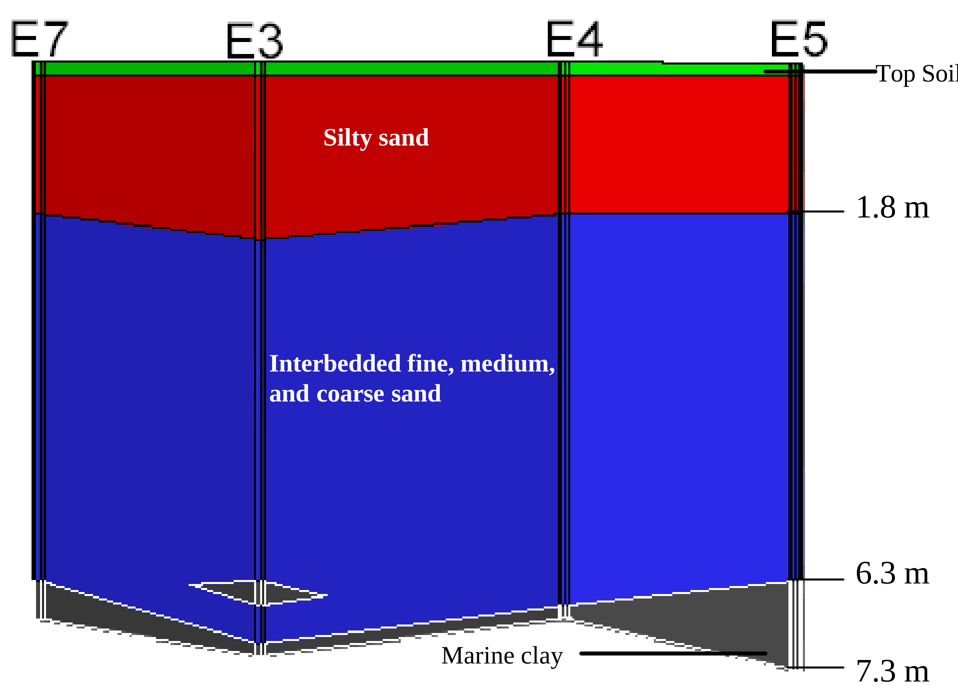



**Figure 3.9:** Cross section through Site 11 showing clay lens at Well E3.

Throughout the Columbia Aquifer at Site 11, there was a series of clay lenses encountered during drilling (see Figure 3.7 to 3.9). At Well I1, the marine clay lens is 0.15 meters thick and the top of the lens is 6.4 meters below the land surface (Figure 3-7). In borehole E3, the marine clay lens is 0.3 meters thick and is 6.3 meters below ground surface (Figure 3.9). The analysis of the borelogs and cross sections show that the overall composition and structure of the Columbia Aquifer and Yorktown Confining unit at site 11 on the NABLC base is consistent the regional characteristics described elsewhere. The average porosity of the treatment zone sediments was 31%. It was measured in the laboratory on intact soil cores obtained from Site 11.

During drilling, a small trough at the contact of the Columbia aquifer and the Yorktown confining unit was encountered. The trough is crossing the site from WNW to ESE and is a depression about 0.5 m deeper than the .surrounding strata. The slope of the trough is directed towards building 3651. PID measurements taken during well drilling increased in soil cores taken from wells closer to the building (E3, see Figure 3.10). Similarly, contaminant concentration in water samples also increased towards building 3651. These observations suggested that DNAPL migrated from the release point (former neutralization tank near well E6) into the trough and towards the building. The trough subsurface feature is common for the upper Yorktown confining unit, but the existence of a trough at Site 11 was not discovered before wells E1, E4, E5, and I1 were already drilled. The original well field constellation was designed on the basis of previous site investigations and hydraulic simulation of an optimized flow field (see Section 4). Upon discovery of the trough, the well field as designed (5-star configuration centered on well I1) had to be modified in the field by adding two additional wells (E6 and E7). The location of these additional wells was dictated by the trough geometry and contaminant distribution. Under the given circumstances the adjusted well field geometry was considered the best-possible constellation for hydraulic control of the CDEF flow field.

*Hydrology*: No aquifer tests were performed at site 11 prior to this demonstration, but the hydraulic characteristics of the Columbia Aquifer were determined at the nearby Site 12 at NABLC. CH2MHILL conducted pumping tests at Site 12 to determine the hydraulic conductivity of the Columbia Aquifer. A constant-rate aquifer test was analyzed and the results were found to be consistent with the unconfined nature of the Columbia Aquifer. The average hydraulic conductivity was estimated to be $9.5 \times 10^{-2}$ cm/d (110 ft/day) (CH2M HILL, 2001). Based on the similarity of geologic materials between Sites 12 and 11, it was assumed that the average hydraulic conductivity for Site 12 was representative for Site 11. The hydrostratigraphic cross sections shown in see Figure 3.11 was compiled from hydrogeologic data gathered during this demonstration. It shows the water table at Site 11 at 1.5 m to 2.1 m (5 to 7 feet) below surface. Groundwater elevations were measured at Site 11 by CH2MHill in September 1999 and November 2000 (Figure 3.12 and Figure 3.13). At Site 11, groundwater flows towards the South and Southeast, based on the groundwater elevations, but may change by approximately $180^0$ during certain times (e.g. under drought conditions prevailing during the demonstration period).

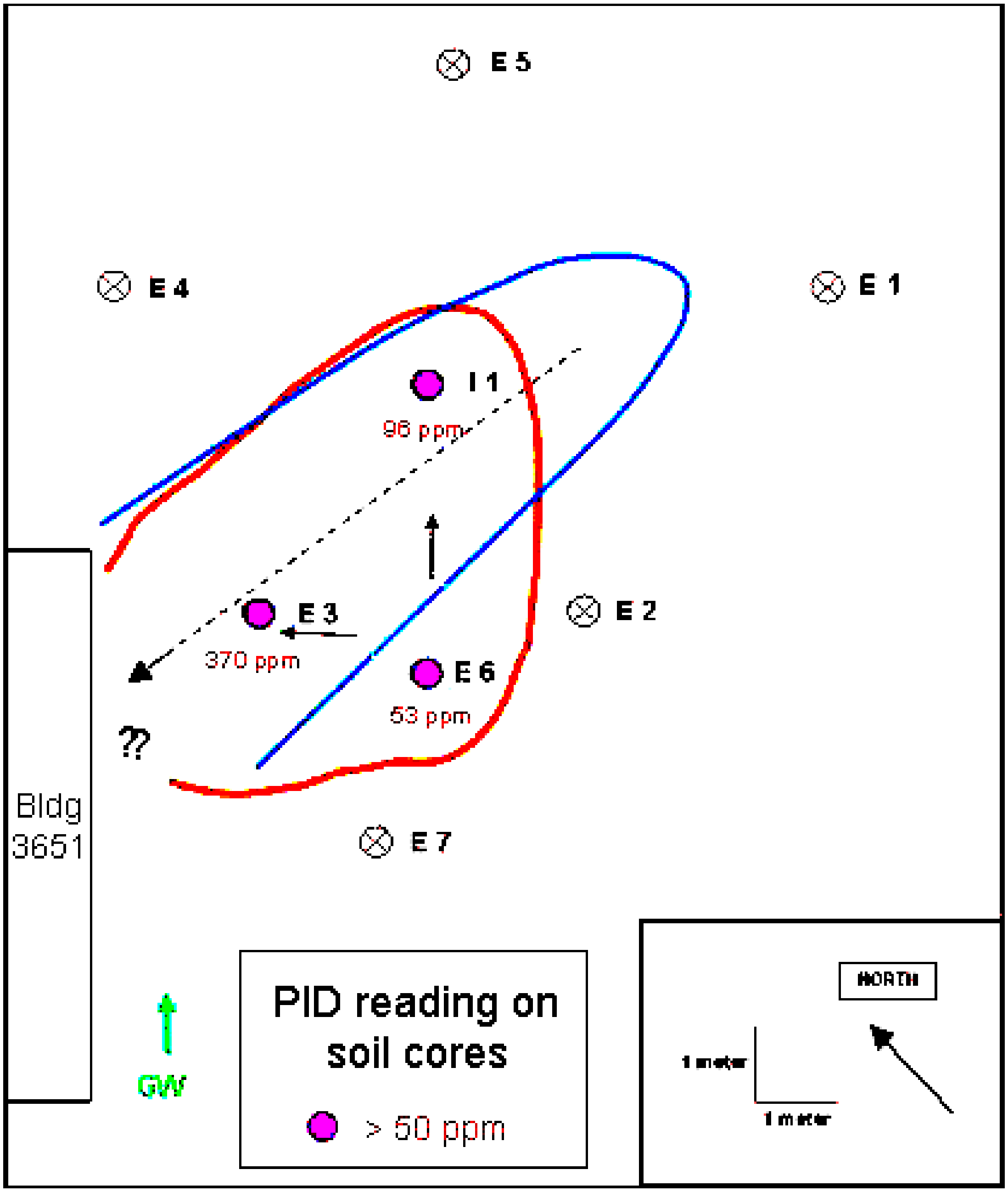



**Figure 3.10:** PID readings and location of the wells drilled for the CDEF demonstration (to scale). PID readings were taken on soil cores during well installation. Also shown (blue line), approximate extent of trough discovered during drilling. The trough axis (dashed line) slopes towards building 3651. The red line marks the approximate extent of the source zone. The former neutralization tank was located near well E6. The groundwater (GW) flow direction at the time of drilling was as indicated, but GW flow direction changed by 180$^{O}$ during the course of the demonstration.

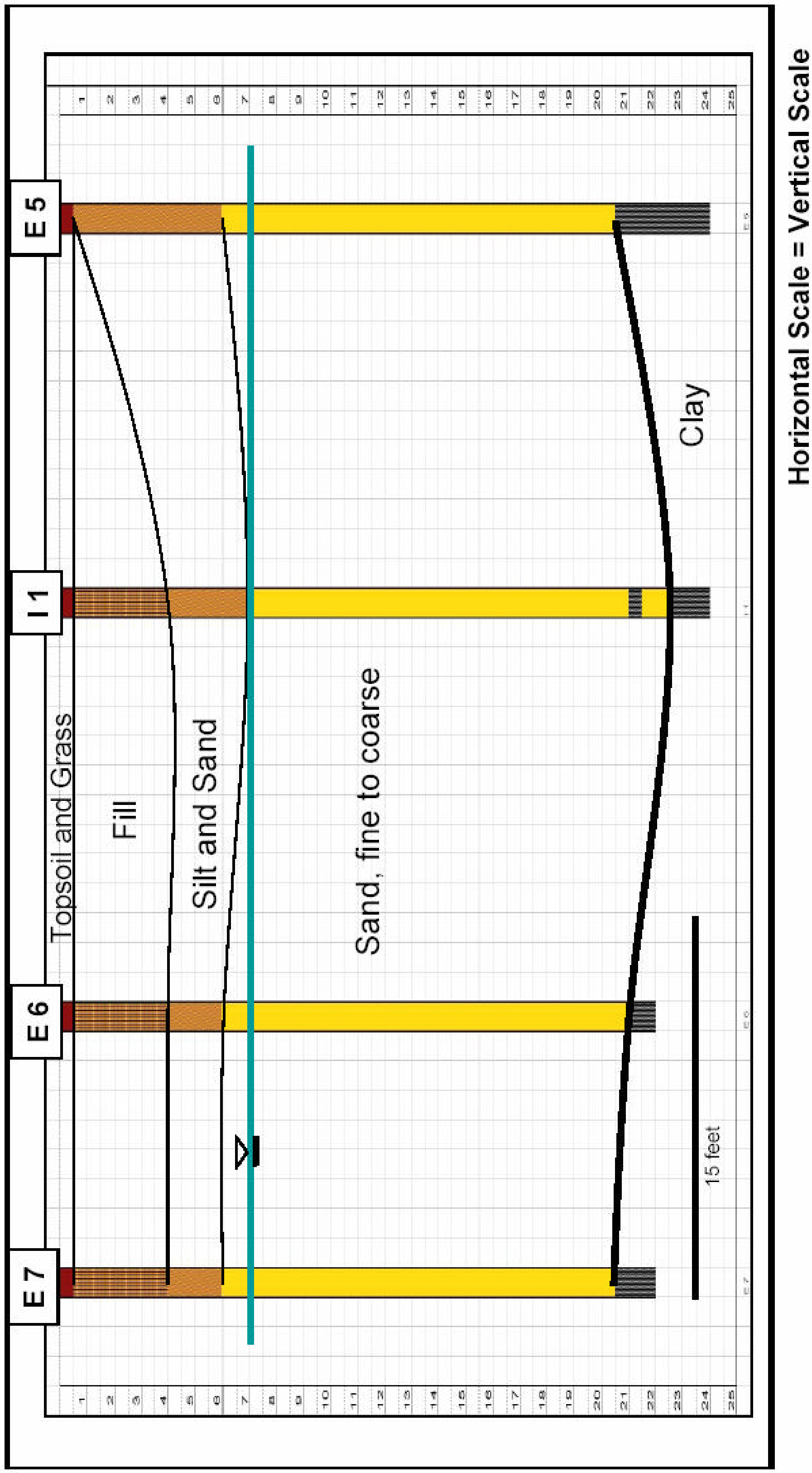



**Figure 3.11**: Hydrostratigraphic cross section through CDEF treatment zone.

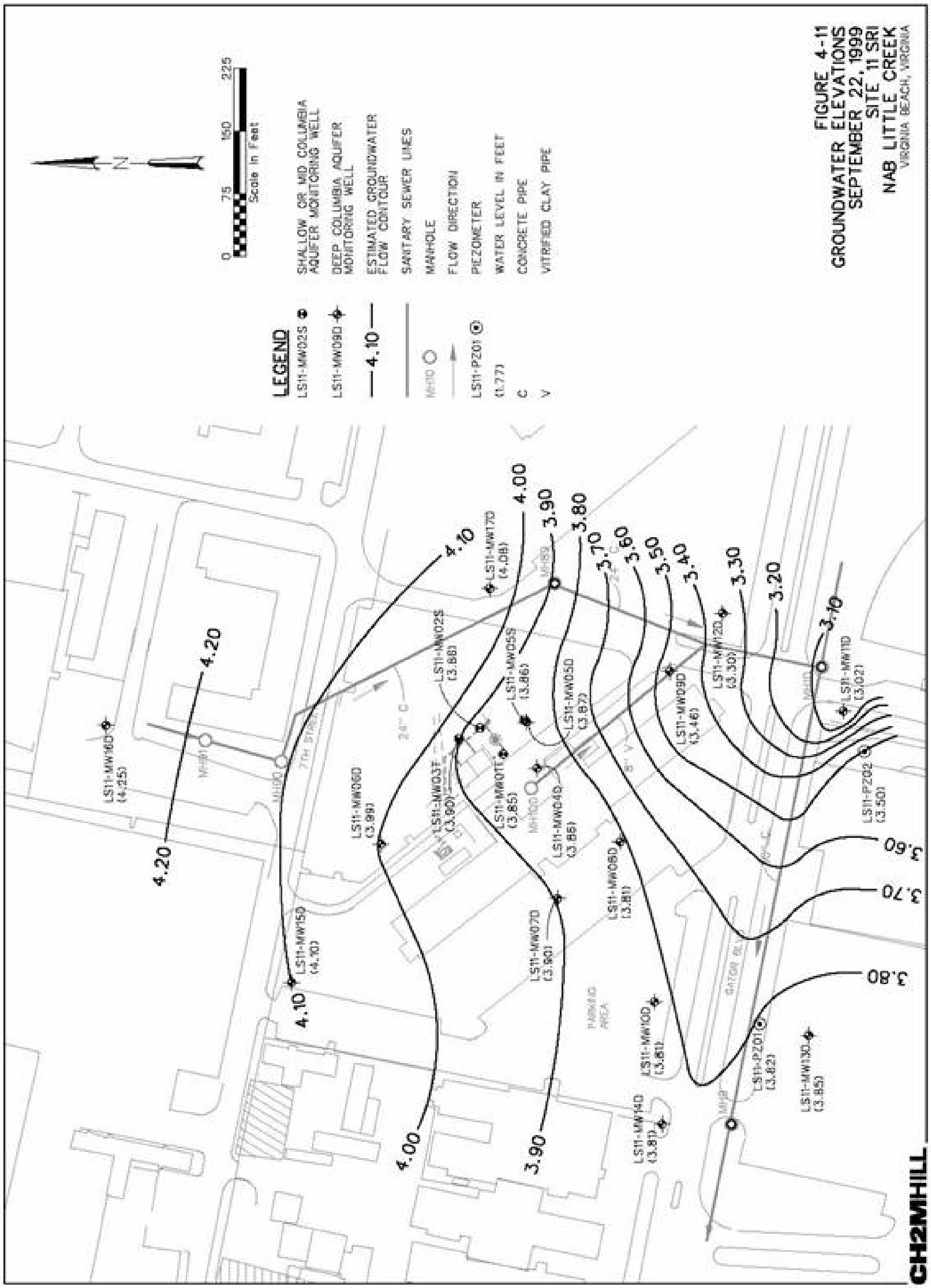



**Figure 3.12:** Groundwater elevations at Site 11 in September 1999 (after CH2MHill, 2001).

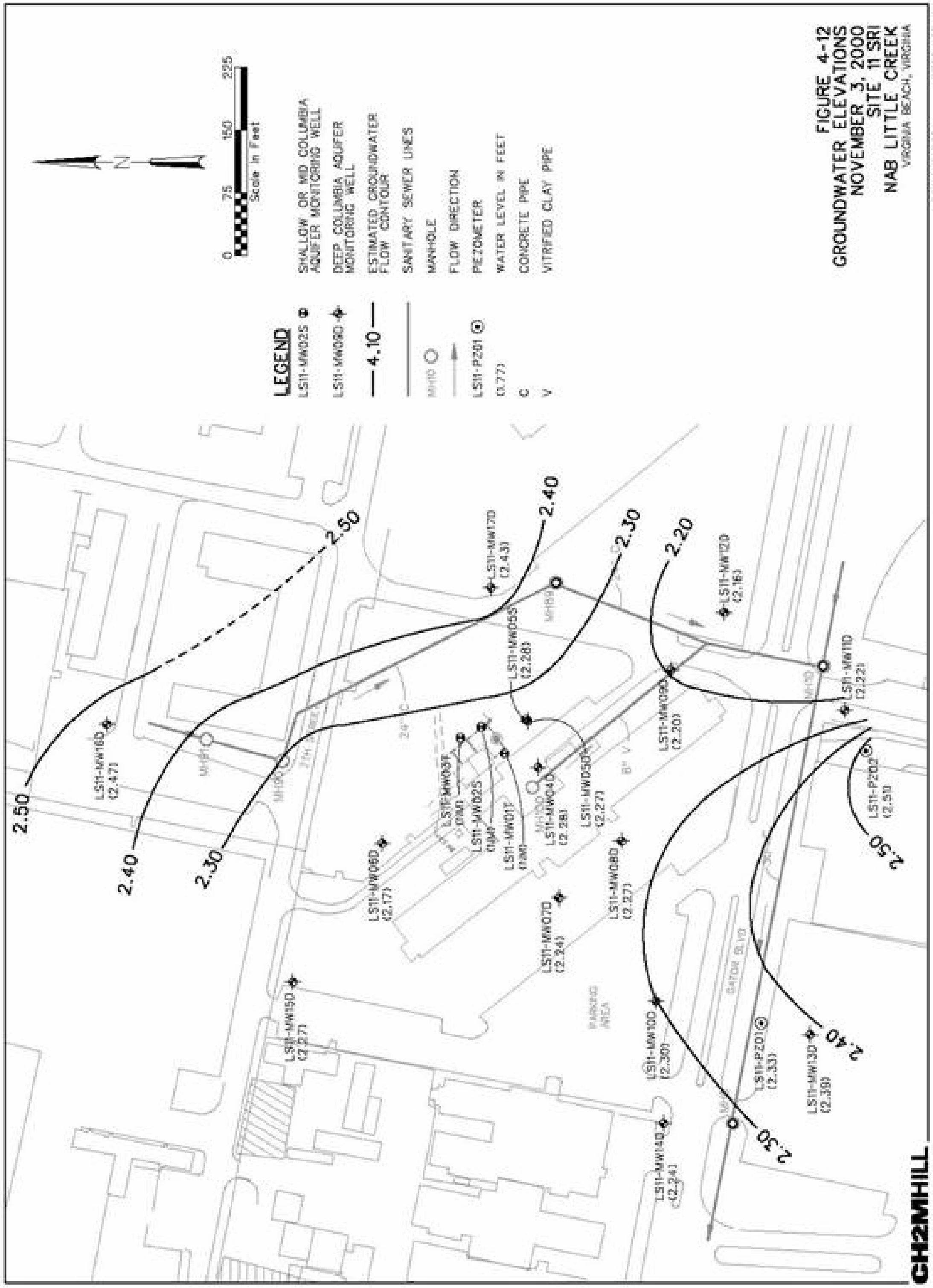



**Figure 3.13:** Groundwater elevations at Site 11 in November 2000 (after CH2MHill, 2001).

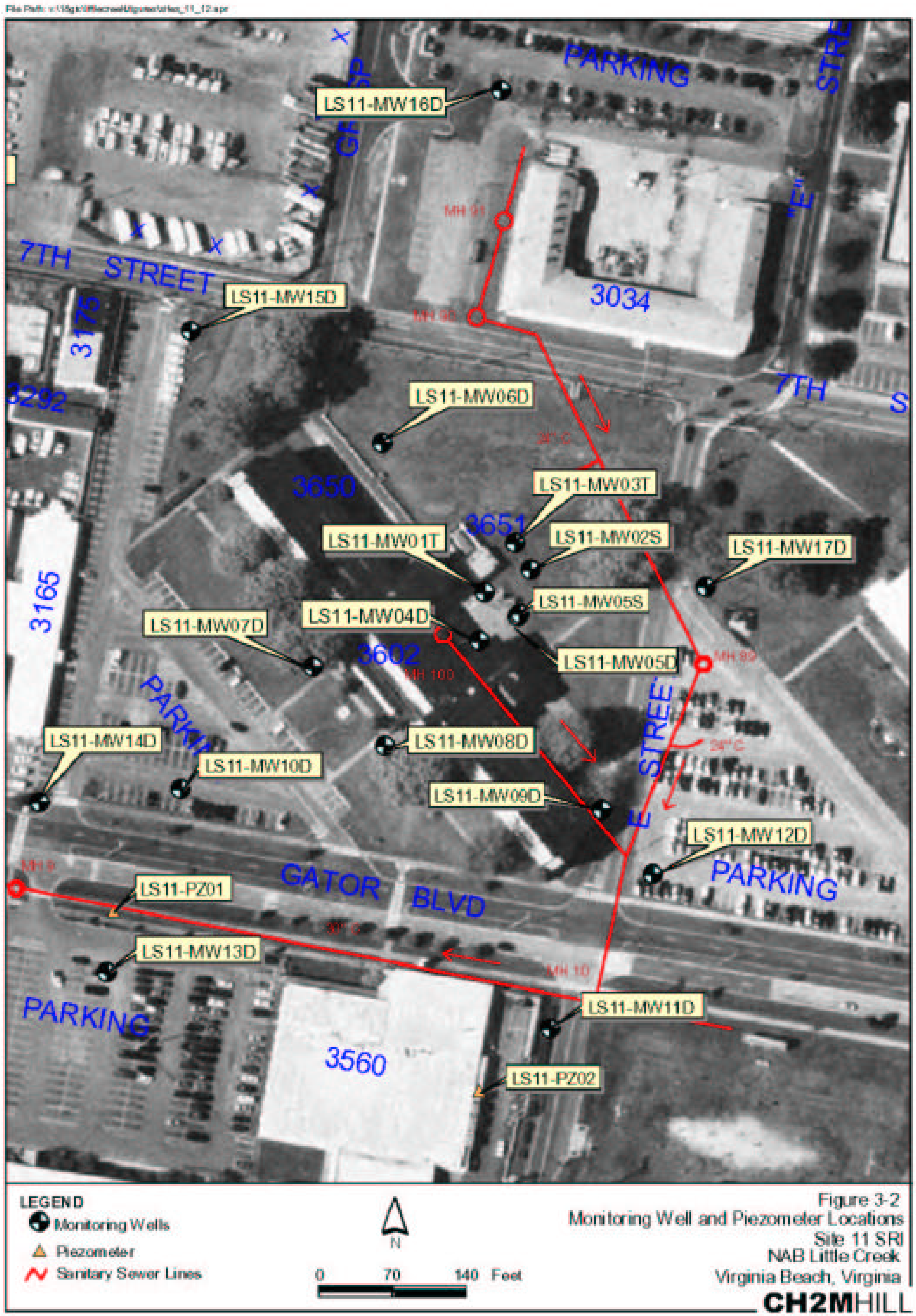



**Figure 3.14**: Red lines mark the location of sewer lines. Building 3650 (center) is the School of Music (after CH2MHill, 2001).

Groundwater flow in the Columbia Aquifer at Site 11 appears to be controlled both by the overall base-wide groundwater flow direction (approximately ENE to WSW) as well as by seepage into a system of leaking sanitary sewer pipes that border the site on the east and south (see Figure 3.14). During the four months duration of this demonstration, groundwater gradients at the site changed from NW to approximately SE. The hydraulic gradient within several hundred feet of the DNAPL spill location varies between approximately $10^{-3}$ and $10^{-4}$ cm/sec, based on the prior groundwater level investigations.

In preparation of the CDEF demonstration, slug tests were conducted in an existing observation well at Site 11. The hydraulic conductivity (K) was measured to be 0.11 cm/sec. This K value was considered very high because it represents very coarse sand and gravel. The subsurface at Site 11, however, consists of mostly medium sand, with some fine sand and silt and localized clay lenses. During the demonstration, several more hydraulic slug tests were conducted on wells drilled for this project (see data in Appendix IV) The slug tests showed that average hydraulic conductivity of the Columbia aquifer was $8.3 \times 10^{-4}$ cm/sec (number of measurements, n = 3), which is a typical value for this type of lithology. An order of magnitude higher hydraulic conductivities (7.9 x $10^{-3}$ cm/sec; n = 2) were determined from sieve analysis of core materials after the Hazen method (Fetter, 1993) (see data in Appendix IV). The analyzed cores, however, were from core materials outside the treatment zone (LS11-MW18 and LS-MW-19, see Figure 3.14). The vertical hydraulic conductivity of the Yorktown confining clays was reported at $3 \times 10^{-8}$ cm/sec (CH2MHill, 2001). The average groundwater flow velocity at Site 11 was approximately 9 cm/day (CH2MHill, 2001). Based on the hydraulic gradient and hydraulic conductivity values given above, and assuming a porosity of 31%, groundwater velocities would range from to 0.3 cm/day and 30 cm/day.

*Nature and Extent of Contamination:* Site-related contamination in the Columbia Aquifer is limited to chlorinated VOCs and one semivolatile organic compound (pentachlorophenol or PCP). The extent of the chlorinated VOC plume has been identified by the results of Geoprobe® and Membrane Interface Probes, and monitoring well groundwater samples (see Figure 3.11 and 3.12). Table 3.1 summarizes the maximum VOC concentrations. Groundwater contamination appears to be confined to the area immediately around the location of the former plating shop neutralization tank extending south to Gator Boulevard (see Figure 3.15). The area of greatest chlorinated VOC contamination is approximately north of the former tank. Monitoring wells installed east of the site across E street and south of the site across Gator Boulevard do not show contaminant concentrations associated with Site 11.

Elevated VOC concentrations were also found south of the former tank area. Because this direction is upgradient of the tank under present site conditions it is possible that these concentrations are from a separate source or due to changing GW flow directions. Three compounds: 1,1-DCE, TCE, and 1,1,1-TCA were present in concentrations that exceeded drinking water standards in at least one well. Detectable chlorinated VOC concentrations are confined to the lower portion of the Columbia Aquifer at the site, as demonstrated by both Geoprobe® and monitoring well groundwater samples that were taken from both the upper portion (8-12 ft bgs) and the lower portion (17-21 ft bgs) of the aquifer). Samples from the sanitary sewers bounding the site to the east and south contained TCE and 1,1-DCE indicating that contaminated groundwater from the site is seeping into the sewers lines, which are located below the water table.

*Fate and Transport of Contamination:* Based on the chemical and physical data gathered for Site 11, it appears likely that the former neutralization tank was the source of the chlorinated VOCs that are currently observed in the Columbia aquifer. Because the neutralization tank has been removed, it is no longer a potential continuing source of contamination. Dense non-aqueous-phase liquid (i.e. TCE) appears to be present in the lower portion of the aquifer at the site, which would be considered a continuing source of contamination.

Only one migration pathway is indicated by the assumed method of disposal and the occurrence of contamination at Site 11. Chlorinated VOCs are migrating through the groundwater flow system in the lower half of the Columbia Aquifer. These compounds are currently being transported from the hot spot near well LS11-MW5D and the former neutralization tank, through the groundwater system via dissolution, advection, and dispersion.

The plume is migrating to the southwest, south, and southeast toward a leaking sanitary sewer line that bounds the plume on the east and south. Discharge of water from the aquifer to the sewer line is occurring at a rate of approximately 10 gpm, which appears to be enough to provide hydraulic control of the aquifer and prevent migration of contaminants beyond the sewer lines. The sanitary sewer at Site 11 flows along Gator Blvd. to NAB Little Creek's main pump station, and then to a publicly-owned treatment works (POTW) for treatment. The abundance of 1,1-DCE in the groundwater provides evidence that 1,1,1-TCA is undergoing degradation. However, there is very little evidence to indicate that 1,1-DCE is further degrading or that the biological degradation of either 1,1,1-TCA or TCE is occurring. Only trace concentrations of cis-1,2-DCE, the primary biodegradation product of TCE, are present.

**3.4 Present Operations**

Site 11 is in the Remedial Investigation (RI) stage of the CERCLA process. Upon completion of the investigation, a Feasibility Study (FS) will be performed to assess multiple alternative remedies for site remediation. The results of this study will be included into the FS to evaluate full-scale implementation of CD to address groundwater remediation. The most favorable alternative will be chosen based upon nine criteria evaluated in accordance with the National Oil and Hazardous Substances Pollution Contingency Plan (NCP 40 CFR 300). The NCP is the basic regulation that implements the statutory requirements of CERCLA (42 USC 9601 et seq.). The nine criteria required by the NCP for a remedy include: overall protection of human health and the environment; compliance with Applicable or Relevant and Appropriate Requirements; long-term effectiveness and permanence; reduction of toxicity, mobility, or volume through treatment; short-term effectiveness; implementability; cost; state acceptance; and community acceptance.

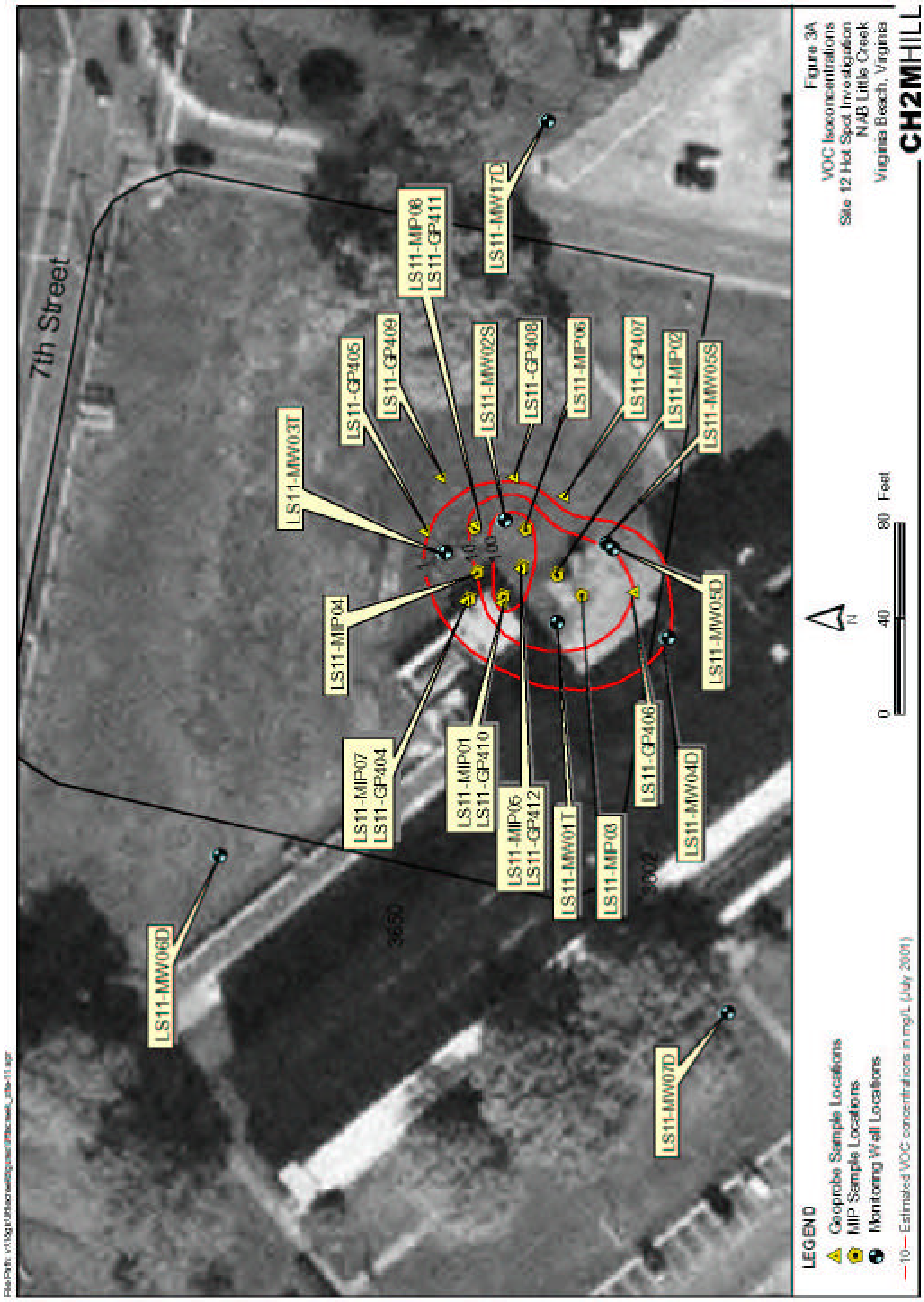



**Figure 3.15:** VOC contour map based on the results obtained during the hot-spot investigation in August 2001. The innermost contour line (100 mg/L VOC) delineates the contaminant source zone and the treatment area targeted for this demonstration (after CH2MHill, 2001).

# 4. Demonstration Approach

## 4.1 Experimental Design

The principal variables of the demonstration were:

1. Cyclodextrin concentration to be injected and extracted into the aquifer
2. Number and location of the injection wells
3. Number and location of the extraction wells
4. Extraction rate
5. Effectiveness of membrane system for CD recovery and VOC treatment

Variables 1 through 4 were optimized based upon a hydraulic simulation of the well field prior to the demonstration. The model used was TOUGH/T2VOC, which is a numerical flow and transport model designed for VOC simulation. The results of these simulations and the optimized well field geometry are shown in Figures 4.1 and 4.2.

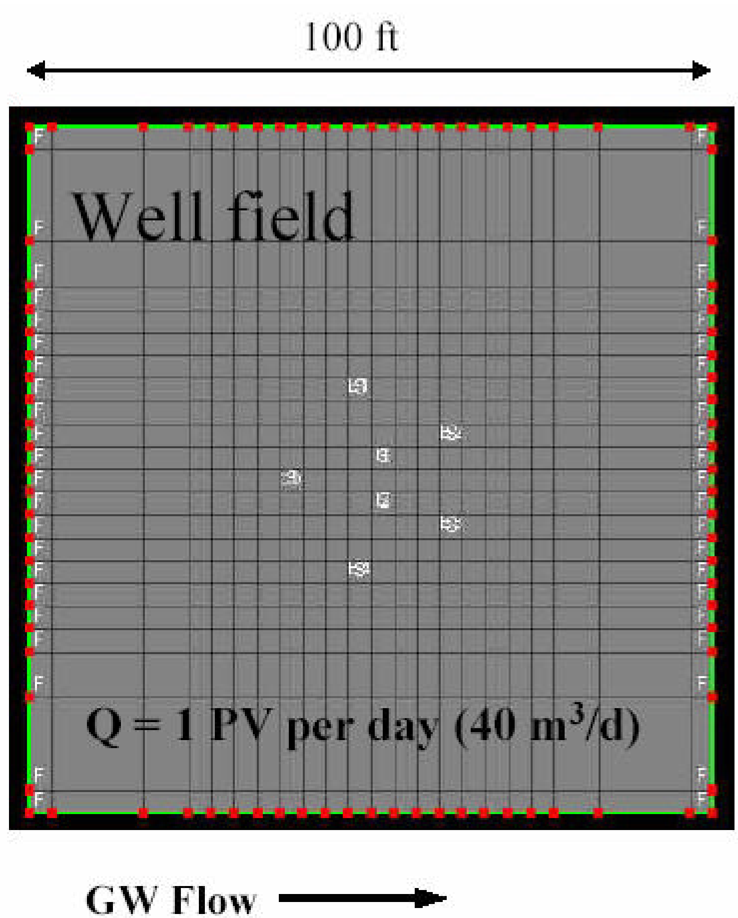



**Figure 4.1:** Layout of the optimized well field as simulated with TOUGH/T2VOC. The well field was centered on two injection wells and was surrounded by five extraction wells.

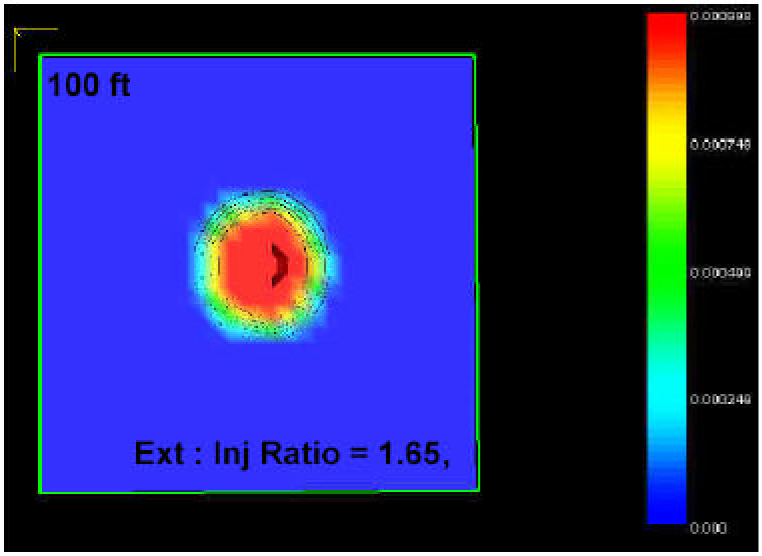



**Figure 4.2.:** Hydraulic simulation of the well field catchment area including optimized extraction to injection ratio. Red colors indicate high CD concentration while blue indicates low concentration.

The tentative well field geometry described in the Demonstration Plan (see Appendix I) differed from the optimized well field geometry shown in Figure 4.1. The geometry and treatment approach outlined in the demonstration plan, i.e., treatment of three segments in succession (see Appendix I: Demonstration Plan), proved to be inefficient based on the simulations with T2VOC. The primary objective of this ESTCP sponsored project was the demonstration and assessment of CDEF and not the full site remediation. Therefore, the actual well field geometry and treatment approach was designed to achieve optimal control of the demonstration parameter and minimize radial displacement of the flushing solution (see Section 4). For these reasons, the well geometry shown in Figure 4.1 and 4.2 was adapted. The well field geometry was further adjusted to the actual field conditions encountered during well installation (i.e., existence of previously unknown trough at the base of the aquifer; see Section 3.3).

In the field, the CD injection/extraction scheme was optimized based on the lessons learned during the precedent tracer tests and a series of hydraulic tests conducted immediately after the tracer tests. The actual treatment scheme realized during the demonstration was part continuous injection/extraction and part push-pull of the CD flushing solution. Dilution of the injected cyclodextrin solution with groundwater and the degree of hydraulic control were the most important factors. They determined the treatment scheme, the actual cyclodextrin, and contaminant concentration at the extraction well. For the demonstration, the target operating CD concentration in the extract was to be between 5 and 10% (wt/wt). The actual CD concentration injected was about 20% (wt/wt) to compensate for dilution of the CD solution during passage through the DNAPL source zone. Another variable was the membrane filter system consisting of the UF unit for CD reconcentration and the PVP unit for VOC removal. Further details about the optimization strategy are provided later in this section and in Appendix I: Demonstration Plan.

| Type of Performance Objective | Primary Performance Criteria | Expected Performance (Metric) | Actual Performance (future) |
|---|---|---|---|
| **Qualitative** | 1. Reduce contaminant source | Smaller source zone | Criterion met |
| | 2. Reduce contaminant mobility | Smaller Plume | Under investigation |
| | 3. Faster remediation | Reach remediation goal faster | Criterion met |
| | 4. Ease of use | Operator acceptance | Criterion met |
| **Quantitative** | 1. Reduce contaminant mass | > 90% | 70% to 81% |
| | 2. Meet regulatory standard | < 5 ppb $MCL_{TCE}$ | Criterion met for all VOCs (treatment effluent) |
| | 3. Recycle cyclodextrin solution | > 5 flushes per molecule | Criterion not met (about 3 flushes per molecule) |
| | 4. Reconcentrate cyclodextrin | Recovery > 80% | Criterion met, although not in continuous operation mode |
| | 5. Remediation time | 3 months | Criterion met (duration of demonstration) |
| | 6. Endpoint criteria | Effluent TCE concentration < 1% initial | Criterion not met (actual: 22% of initial TCE conc.) |
| | Maintenance | Downtime < 10% of total operating time | Criterion met |
| | Reliability | Downtime < 25 to 50% of total operating time (during Demonstration) | Criterion met |
| | Factors affecting technology performance | 1) Flow rate: 18,000 gpd<br>2) Feed rate:<br>3) CD concentration: 10%<br>4) Temperature: $17^0$C<br>5) Soil type: Sand (boring logs)<br>6) Particle size distribution: medium Sand (sieve analysis)<br>7) Soil homogeneity: homogenous (boring logs)<br>8) GW pH: near pH 7<br>9) Dissolved Oxygen: 50% saturated<br>10) Other Contaminants: no interference | 7,200 gpd<br><br>3 to 10% (I/E), 5 to 33% (PP)<br>23 to $25^o$C<br>Silty sand<br>Medium sand and clay lenses<br>Heterogeneous (clay lenses and trough)<br>pH between 6 and 7<br>DO < 5%<br>Iron precipitation |

**Table 4.1** Objectives that provided the basis for evaluating the performance and cost of the cyclodextrin technology.

## 4.2 Performance Objectives

Qualitative and quantitative objectives were defined prior to the CDEF demonstration (see Appendix I: Demonstration Plan) to serve as the basis for evaluating the performance and cost of the cyclodextrin technology. Expected and actual objectives are summarized in Table 4.1.

This pilot test was performed under the CERCLA (42 USC 9601 et seq.) statutory framework. As such, compliance with federal, state, and local statutes was maintained as Applicable or Relevant and Appropriate Requirements (ARARs). ARARs for this site included, but were not limited to the Resource Conservation and Recovery Act (RCRA, 42 USC 6901 et seq.), the Federal Facilities Compliance Act (FFCA, 42 USC 6901 Note, 6908), the Clean Air Act (CAA, 42 USC 7401-7671q.), Executive Order 12088 (Federal Compliance with Pollution Control Standards), Executive Order 12580 (Superfund Implementation), the Clean Water Act (CWA, 33 USC 1251-1387), the Safe Drinking Water Act (SDWA, 42 USC 300f et seq.), and the Virginia Water Quality Standards (9 VAC 25-260-5 et seq.). These regulations drove the performance criteria listed in Table 4.1. Under these provisions, maximum contaminant levels (MCL, SDWA) for dissolved VOC compounds (and other) are established. A complete list of current MCLs can be seen at http://www.epa.gov/OGWDW/mcl.html. The MCL would be the remediation goal for groundwater clean up at Site 11 and would need to be reached before regulatory closeout of the site could be achieved. The CAA regulated discharge from the air stripper. The CWA and Virginia Water Quality Standards regulated discharge requirements for water treated below the MCL.

In the demonstration plan (see Appendix I), the technology demonstration was deemed successful if cyclodextrin enhanced flushing removed (1) at least 90% of the contaminant mass, (2) leading to a smaller plume and shorter remediation, (3) is a reliable, versatile, easy to use method, (4) with no undesirable side effects, such as generation of process waste or hazardous compounds, and (5) is cost effective. The effectiveness of the demonstration was evaluated based on the performance criteria listed in Table 4.1 and applying the performance confirmation methods summarized in Table. 4.2. A detailed description of the performance parameter is provided in Table 4.3. A discussion of the actual performance of CEDF during this demonstration is provided in the following sections.

**Table 4.2:** Summary of performance criteria.

| Performance Criteria | Expected Performance Metric (pre demo) | Performance Confirmation Method |
|---|---|---|
| **PRIMARY CRITERIA (Performance Objective) (Qualitative)** | | |
| Contaminant Mobility | Reduced smaller plume | Monitoring wells LS11 -MW02, -MW01T, -MW04D, -MW05D |
| Faster Remediation | Endpoint attained faster | Monitoring wells LS11 -MW02, -MW01T, -MW04D, -MW05D |
| Ease of Use | Minimal operator training required | Experience from demonstration operations |
| **PRIMARY CRITERIA (Performance Objective) (Quantitative)** | | |
| Hazardous Materials<br>- Generated | None<br>(except for PTT which is not an intrinsic part of CDEF technology) | Analysis for possible toxic degradation products |
| Factors Affecting Technology Performance | | |
| Flow rate | 64 $m^3$/d (18 000 gpd) | Certified ABB flow meter (Accuracy +/- 3%) |
| Feed rate | 0.5 $m^3$ / hr | Certified ABB flow meter (Accuracy +/- 3%) |
| CD Concentration | 20 to 40% at injection well<br>5 to 10% at extraction well | TNS-complexation (Fluorescence Spectrophotometer) and Total Organic Carbon analysis (TOC) |
| Soil type | > 100 ft/d hydraulic conductivity (medium sand with some silty clayey strata) | Pre demo slug test |
| Particle Size Distribution | Fraction < 0.063 mm (very fine sand) is less than 10% | Sieve Analysis of cores (ASTM D422-63 method) |
| Soil Homogeneity | Strata of predominantly sandy material > 90% of screened interval | Thickness of strata in soil boring profile |
| GW pH | pH varies between 6 and 8 | Orion pH meter (Accuracy +/- 5%) |
| Dissolved Oxygen | DO varies between 50 to 90% saturation | YSI 55 DO meter (Accuracy +/- 5%) |
| Target Contaminant | | |
| % Reduction | Reduce TCE by 90% | Mass balance in combination with pre- and post demo PTT |
| Regulatory Standard | Attain TCE MCL (5 ppb ) | UA Method (GC-FID), Duplicates, spikes, trip, blanks, RPD<60%, Recovery>90%, Complete>95% |

| SECONDARY PERFORMANCE CRITERIA (Performance Objective) (Quantitative) | | |
|---|---|---|
| Process Waste | | |
| Generated | None (except PTT tracers which are not an intrinsic part of CDEF technology) | Observation |
| Plume Size | Smaller | Monitoring wells LS11 -MW02, -MW01T, -MW04D, -MW05D |
| Reliability | | |
| Downtime due to equipment failure | < 5% of demonstration time | Record keeping |
| Safety | | |
| Hazards | None | Demonstration experience |
| Protective clothing | None | Demonstration experience |
| Versatility | | |
| Continues operation | Yes | Demonstration experience |
| Intermittent operation | Yes | Demonstration experience |
| Other application | Yes – push-pull injection | Demonstration experience |
| Maintenance | | |
| Required | Activated carbon exchange<br>Filter press clean out<br>CD storage tank exchange | Demonstration experience |
| Scale-Up Constraints | | |
| Engineering | Operating space | Monitoring during demonstration operation |
| Flow Rate | Available equipment capacity | |
| Contaminant Concentration | None | |

**Table 4.2:** Summary of performance criteria (continued from previous page).

**Table 4.3**: Description of the primary and secondary performance criteria

| Performance Criteria | Description | Primary or Secondary |
|---|---|---|
| Contaminant Reduction | The target contaminant to be cleaned up are DNAPL's (primarily chlorinated solvents) | Primary |
| Contaminant Mobility | TCE, some 1,1,1-TCA and degradation products thereof | Primary |
| Hazardous Materials | Besides traces of the original contaminants, no other hazardous material will remain | Primary |
| Process Waste | 1) Cyclodextrin solution left over after completion of demonstration<br>2) Cyclodextrin solution left in aquifer and filtered out soil particles<br>3) PTT solution – extracted solution will contain less than 50 mg/L of 2,2-dimethyl-3-pentanol, 6-methyl-2-heptanol, and isopropyl alcohol After air stripping, only residual concentrations will remain, which can be discharged into the base wastewater treatment system. These tracers are miscible with water, so no measurable concentrations will remain in the subsurface after the test. Contaminant concentrations in the PTT fluid after air-stripping is expected to be less than the MCL. | Secondary |
| Factors Affecting Technology Performance | *1) Flow rate*: higher flow rate decreases remediation time, but requires larger equipment capacity (e.g. air stripper etc.). Anticipated flow rate permits flushing of one pore volume per day per segment<br>*2) Feed rate*: higher feed rate reduces clean up time. Feed rate appears not limited by soil permeability.<br>*3) CD concentration*: higher concentration increases contaminant solubility enhancement and shortens clean up time. CD at extraction well head(-s) is a function of feed concentration and dilution.<br>*4) Soil type*: higher permeable soils require less clean-up times. Demonstration site soil is very permeable.<br>*5) Particle size distribution*: High clay fraction decreases permeability, causing longer remediation times. Little clay content as demonstration site expected.<br>*6) Soil homogeneity*: stratification may cause contaminant mass transfer limitations and longer clean up times. Little stratification at demonstration site expected.<br>*7) GW pH*: no influence expected at test (pH 6 to 7.5).<br>*8) Dissolved Oxygen*: Higher DO levels may speed up CD degradation. Air stripping enhances DO content.<br>10) *Other contaminants*: only chlorinated solvents, no effects on CD performance expected. | Primary |
| Reliability | The cyclodextrin technology is relatively robust because it relies heavily on standard industrial equipment and processes. Potential breakdowns should be associated with wear-and-tear of the equipment only. Care has to be taken when process water contains fines or minerals that are know to precipitate from solution (e.g. lime of iron salts). Precipitates or fines may cause cloaking and decreased equipment performance (especially when using an air stripper). Sensitivity to environmental conditions is low, except in cases where prolonged sub-freezing temperatures require insulation of pipes and other surface equipment (incl. cyclodextrin stock solution). | Secondary |

| | | |
|---|---|---|
| Versatility | Cyclodextrin has been found to increase the solubility of a great variety of organic contaminants (incl. petroleum hydrocarbons, polycyclic aromatic hydrocarbons, pesticides etc.). Therefore, the use of this technology is not limited to the removal of chlorinated solvents alone. However, non-volatile compounds (such as PAH) cannot be removed by air stripping. These compounds require alternative removal strategies (e.g. activated carbon filtration etc.). Low permeable soils (e.g. clays) or stratification limits the versatility of this technology because of limited mass transfer from these zones. | Secondary |
| Maintenance | Routine maintenance of filter press, air stripper, and membrane filter is necessary to assure optimal performance. Maintenance frequency is site specific, but less than 10% downtime of an established treatment system is expected. Once a system is fully operational, the level of training for the maintenance personal is minimal, i.e. restricted to regular health&safety and equipment specific maintenance training. However, a certified electrician should be available on short notice in case of a major electrical problem.<br><br>Standard operation of the cyclodextrin flushing technology requires periodic sampling of the feed CD concentration and the concentration in the extracted water. The analytical method is simple and can be carried out on site in real time. Also, the target contaminant concentration (here: TCE) must be monitored on a periodic basis. Depending on the target contaminant, samples must be sent to a laboratory of analysis. Finally, if activated carbon filters are used to remove volatiles, the removal performance of those filters has to be monitored. A PID is sufficient for many compounds. | Secondary |
| Scale-Up Constraints | Scale up is limited only by site constraints (= availability of operating space) and the capacity of the treatment equipment (primarily the membrane filtration unit). However, more than one membrane filter, for example, can be operated parallel if necessary. On a relatively small site, a mobile treatment unit (as being used for this demonstration) may be advantageous. For larger sites, a fixed unit may work more efficient. Other issues involve acquisition versus equipment rental. If many sites on the same property need to be treated, equipment acquisition is more economical. | Secondary |
| Safety | Besides the inherent safety issues when working at a contaminated site (i.e. OSHA certifications), no other hazards are associated with the technology demonstration. No need for protective clothing. | Secondary |

**Table 4.3**: Description of the primary and secondary performance criteria (continued from previous page).

### 4.2.1 Qualitative Performance Objectives

The expected qualitative performance metrics were (1) smaller source zone as a result of CDEF treatment, (2) reduced contaminant mobility and smaller plume, (3) shorter remediation time, and (4) demonstrated ease of use of CDEF, i.e., minimal operator training, and leads to rapid operator acceptance of this remediation technology. The qualitative performance objectives (1) through (3) were metered against wells that were installed by the Navy prior to this demonstration (Monitoring wells LS11 -MW02, -MW01T, -MW04D, -MW05D). Objective (4) was evaluated based on the experience gathered during the demonstration at NABLC.

### 4.2.2 Quantitative Performance Objectives

#### 4.2.2.1 Reduction of Contaminant Mass

The desired quantitative performance metric of CDEF was reduction of the DNAPL mass by 90% or more. The DNAPL mass before and after the CDEF was determined with pre- and post-PTT. The comparison of the two PTT's in combination with the calculated contaminant mass recoveries achieved during CDEF served as the measures of this performance objective. Based on this metric, between 70% and 81% of the DNAPL mass was removed during the entire demonstration, which is 9% to 20% short of the anticipated performance objective (90% DNAPL mass removal).

#### 4.2.2.2 Discharge Meets Regulatory Standards

The MCL for all contaminants was the required performance objective for any CDEF discharge leaving the site via a storm drain. This performance metric was independently controlled by NABLC and EPA although it is not generally required by federal regulations. An air stripper and a PVP system were implemented to reach this performance goal. For these treatment system to be efficient, the TCE/VOC removal should be 90% or greater at a flow rate not lower than 5 gpm. This performance objective was met.

#### 4.2.2.3 Recycle and Reconcentrate CD Solution

The desired performance metric for CD recycling was 5 flushes per CD molecule. The performance objective of CD reconcentration/recovery was 80%. A continuously operating UF system was designed as the principal way to achieve these objectives. To be efficient, the UF system must remove 90% or more cyclodextrin relative to the cyclodextrin concentration in the feed. In order to run in-line in the extraction/injection system, the UF unit needs to operate at a constant flow rate of 5gpm or above. Otherwise, batch mode operation is required. The CD recycling criterion was met, although in batch mode only. The CD recycling criterion was met when applying the push-pull (CPPT) treatment approach, but not in line-drive (I/E) mode.

#### 4.2.2.4 Remediation Time and Endpoint Criteria

The objective was to reach < 1% of the pre-CDEF TCE effluent concentration in 3 months. The quantitative metric for this performance goal was the comparison of pre-CDEF contaminant concentrations in groundwater from pre-existing wells, i.e., wells that were installed for plume delineation prior to this demonstration (Monitoring wells LS11 -MW02, -MW01T, -MW04D, -MW05D). Samples were collected from these wells in July 1999 and reported by CH2MHill in the Supplemental Remedial Investigation for Site 11 (CH2MHill, 2001). Because of time constraints at the end of the demonstration, not all of the CD was recovered. Therefore, water samples collected from the monitoring wells immediately after CDEF still contained >1% CD. For this reason, these samples were not used for quantification of the achieved remediation levels. Instead, water sampled and analyzed by CH2MHill in January 2003, i.e, 4 months after the conclusion of CDEF, were used for comparison. When these water samples were collected, the CD concentration had decreased below 0.6% on average. Analysis of CH2MHill water samples demonstrated that the reduction of up to 81% of the DNAPL mass resulted in a 78% decline of the aqueous TCE concentration. Based on this result, the performance objective (>99% less TCE in water after CDEF) was not met.

#### 4.2.2.5 Maintenance and Reliability

The demonstration was planned as a full-scale operation under unconstrained conditions, i.e. no hydraulic barriers surrounding the test site. It included (1) the subsurface DNAPL remediation with CDEF and (2) the aboveground treatment and recovery of the extracted solutions. The principal components of the system were:

1. Injection wells
2. Extraction wells
3. Filter press
4. Air stripper with activated carbon filter
5. Membrane filter (UF and PVP)
6. Cyclodextrin storage tanks and mixing tanks

The CDEF system was designed to operate continuously, except for down time for maintenance and repairs – if necessary. The components of the subsurface system that required regular maintenance included submersible pumps and the wells. The latter clogged several times during the demonstration and was the main cause for system failure. With regard to the aboveground system, regular maintenance was required of the sand filter, the air stripper and PVP, and the UF system. Occasional cleaning of clogged valves and water filters was conducted when necessary (approximately once per month). The duration and degree of maintenance related downtime was recorded. The reliability of the system was also determined, i.e., records were taken regarding the operating status of each component of CDEF. Prior to the demonstration, it was estimated that the actual operating time would be between 50 to 75% (two to three months) over the duration of the demonstration (see Appendix I: Demonstration Plan).

### 4.2.2.6 Factors Affecting Technology Performance

Factors that affected the CDEF performance, such as flow rates or CD concentration, were quantified in the field using the appropriate field equipment (see Appendix I: Demonstration plan for description of methods). Only the particle size distribution was measured in the lab (see section 3.3).

## 4.3 Physical Setup and Operation

The CDEF demonstration at NABLC was carried out in several stages from June though September 2002. A process scheme is shown in Figure 4.3. Figure 4.4 shows a plan of the site setup relative to building 3651. Table 4.4 summarizes all tests conducted at the site, including all PTTs and push-pull tests, wells in which the tests were conducted, and dates.

**Table 4.4: Site activities and test durations, including wells operated (na: not applicable)**

| Activity or Test | Start Date | End Date | Wells Operated |
|---|---|---|---|
| Kick-off meeting in Virginia Beach, VA | 06/03/02 | | na |
| Well drilling and development | 06/04/02 | 06/10/02 | na |
| Plumbing well field | 06/14/02 | 06/21/02 | na |
| Hydraulic testing of wells (slug tests) | 06/21/02 | 06/30/02 | all eight wells |
| Set-up of field equipment | 06/17/02 | 07/14/02 | na |
| Pre-CDEF PTT | 07/06/02 | 07/22/02 | Injection: I-1<br>Extraction: E-2, -3, -6<br>Hydraulic control: E-5 |
| PVP tests | 07/07/02 | 08/28/02 | na |
| UF tests | 07/15/02 | 09/14/02 | na |
| CDEF system shake-down | 07/22/02 | 08/09/02 | E-3 (CPPT-1 and CPPT-2)<br>I-1 (CPPT-3)<br>E-6 (CPPT-4 and CPPT-5) |
| Line-drive CDEF test (I/E) | 08/10/02 | 08/20/02 | Injection: E-2, E-7, E-6 (initially)<br>Extraction: I-1, E-3, E-6 (since 08/14/02)<br>Hydraulic control: E-4 |
| Multi-well push-pull tests (CPPT) | 08/23/02 | 08/31/02 | I1, E3, E6 (CPPT-6, -7, -8) |
| Source zone flushing in preparation for post-CDEF PTT | 09/10/02 | 09/17/02 | Extraction: E2, E3, E6<br>Injection: E1, E5 |
| Post-CDEF PTT | 09/17/02 | 09/27/02 | Injection: I1<br>Extraction: E2, -3, -6<br>Hydraulic control: E-1, -5 |
| Site demobilization | 09/27/02 | 10/02/02 | na |

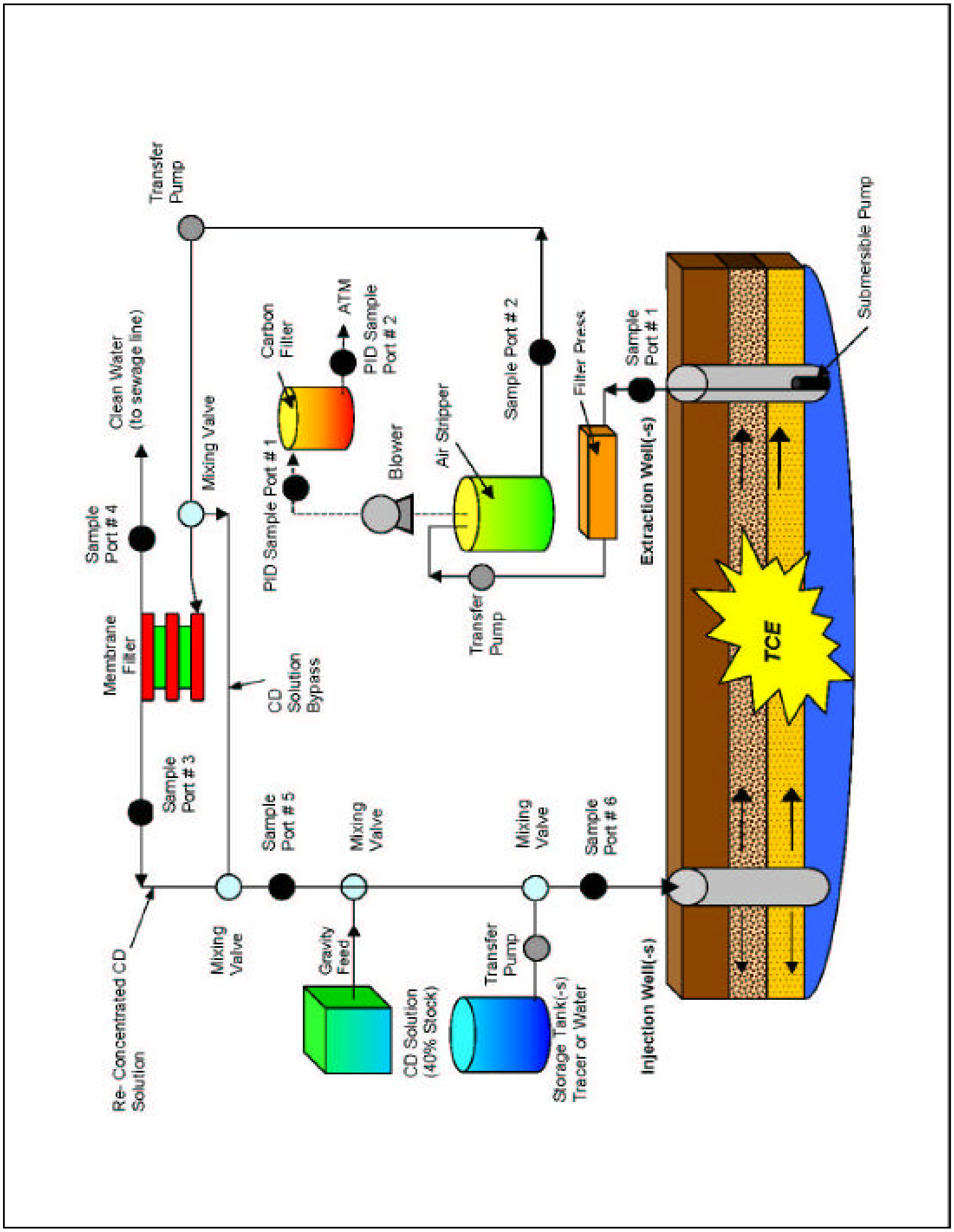



**Figure 4.3:** Process scheme used during the CDEF demonstration.

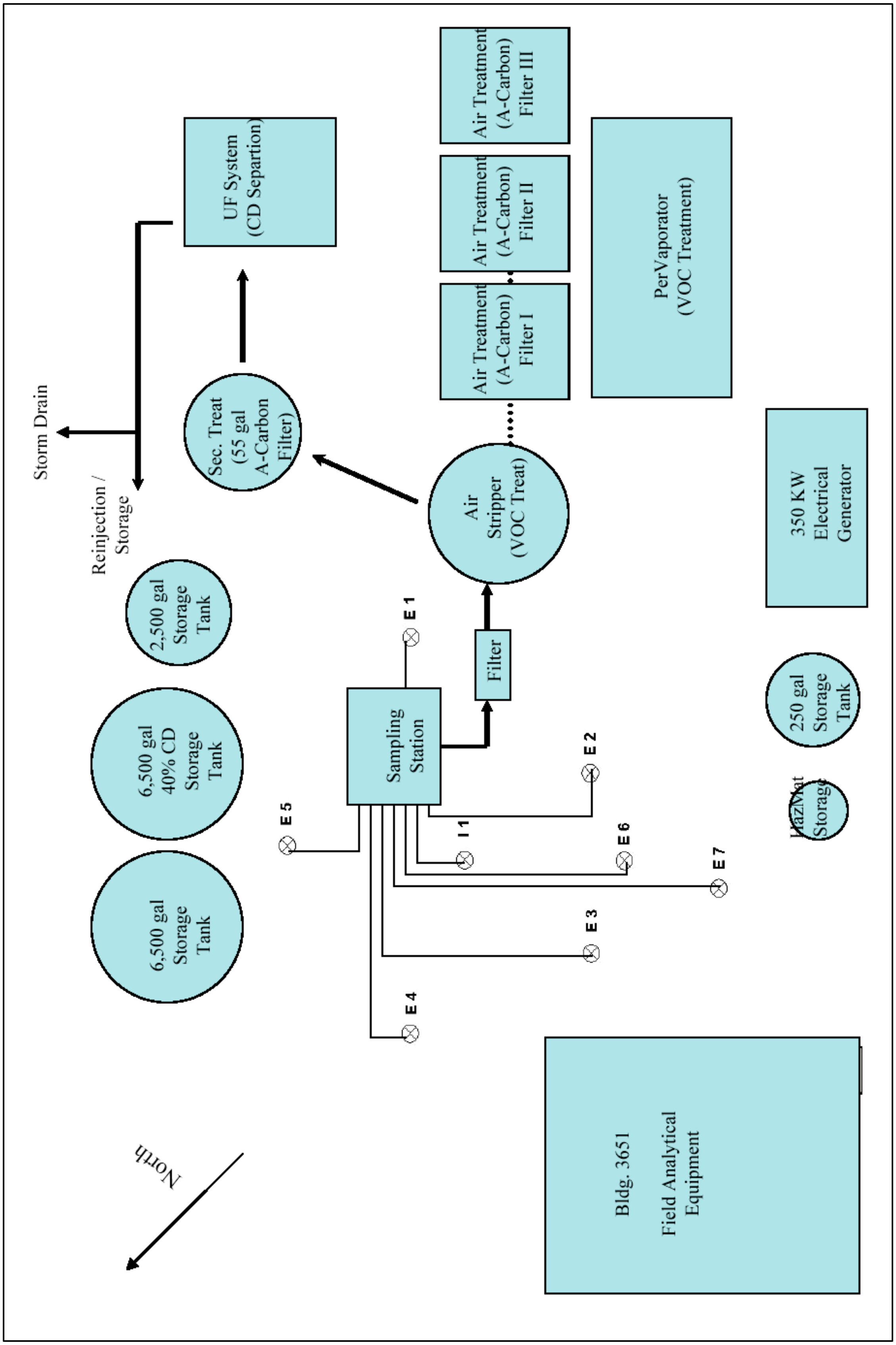



**Figure 4.4:** Aboveground system layout at Site 11.

The Gantt chart (Table 4.5) shows the planned and actual dates and durations of each phase of the demonstration. The long-term monitoring of the post-trial plume was not included for scale reasons. The anticipated duration of the long-term monitoring is one year from the end of the demonstration (until early fall 2003).

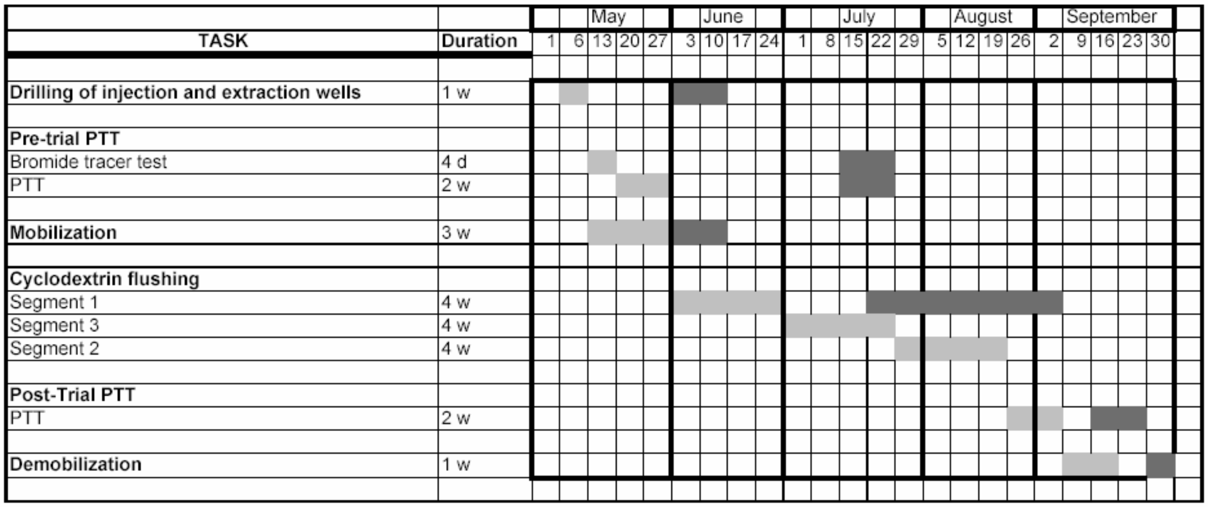



**Table 4.5**: Planned (light gray) and actual dates (dark) and durations of each phase of the demonstration.

Following site setup, a 10-day pre-CDEF partition tracer test was conducted in mid July – approximately 4 weeks behind schedule. The delay was caused mainly by the local POTW, which withdrew permission to discharge treatment effluent to their system. The POTW withdrew initial consent to discharge due to a policy in-place that restricted acceptance of any treated water from a site listed under the Superfund's National Priorities List (NPL). Since Site 11 was part of the IRP at NABLC, which is listed on the NPL, the POTW could not accept effluent from the study into their POTW. In response, the field activities were curtailed while the Virginia Department of Environmental Quality (VADEQ) was approached for a concurrence to discharge to a storm water conveyance. VADEQ granted the discharge during early July and the field test resumed with the pre-PTT.

The demonstration plan (see Appendix I) stipulated that before the injection of the cyclodextrin solution, a pre-trial tracer test was to be conducted to validate the optimal flow system as determined by the hydraulic simulations. Because of the delays caused by renegotiating the discharge issue, the tracer test was combined with the PTT. The tracer used was potassium bromide at a concentration of 1000 mg/L. The dilution, the bromide mass recovery, and recovery times was calculated from the extracted bromide concentration in combination with the pump rate. The bromide concentration was determined on-site with an ion-selective electrode (see Appendix I: Demonstration Plan).

The injection and extraction of CD solution began immediately after the end of the pre-demonstration PTT and bromide tracer test and lasted through end of August. During these 7 weeks of CDEF operation (about 5 weeks less than planned), about 1/3 of the time was spent to testing the well field and optimizing the CD injection and extraction rates. The remaining time was spent conducting injection/extraction (I/E) tests and systematic push-pull (CPPT) test. Push-pull tests were not considered in the demonstration plan. The switch from an I/E to CPPT was in response to (1) poor hydraulic control during the I/E tests due to well clogging, (2) lower than expected CD concentrations and recovery rates, and (3) limitations of the above ground treatment system (in particular, lower than expected UF flow rates). Following the CDEF demonstration, a second, post-PTT was conducted for 10 days in mid September. Two additional conservative tracer, fluorescein and deuterium, were added to the tracer list to avoid possible interference of bromide tracer left over from the previous tracer test. The site was demobilized by the end of September and handed back to NABCL on October 2nd, 2002.

The site setup included the following activities:

- Drilling of eight injection/extraction wells
- Installation of submersible pumps and electrical controls
- Installation of sample ports, flow valves, and sand filter
- Setting up two 6.500 gal storage tanks, one 2,500 mixing tank, and one 250 gal PVP effluent storage tank (incl. containment berms)
- Setup and calibration of on-site analytical equipment (gas chromatograph (GC), total organic carbon analyzer (TOC) in building 3651)
- Connection of air stripper and PVP system to flushing system
- Hookup of activated carbon filters units to air stripper
- Connection of UF system
- Connection of 350 KW diesel-electric generator (480 Volt)
- Plumbing of flushing solution delivery system, including discharge pipes and two barrels of activated carbon for polishing effluent water

All field equipment, except the analytical instruments, was stored outside. No protective housing for the field equipment was necessary. During two major storm events, the site flooded and was temporarily covered under more than 0.3 m of water. The site setup is depicted in Figure 4.4. Pictures of various system components are shown in Appendix III.

The PVP system was damaged during setup. A service technician was able to fix the PVP to permit at least limited assessment of this VOC treatment technology. Due to the damage that could not be fixed in the field, the PVP did never reach its full treatment capacity. Therefore, it was used to treat extracted solutions in batch mode only.

Initial extraction rates during the injection/extraction (I/E) test on wells I1, E3, and E6 were set between 1.2 gpm and 1.5 gpm per well. Lateral hydraulic control was achieved by injecting tap water into wells E5 and E1 and extracting from well E4 during the CD injection. The tap water did not contain measurable VOC concentrations or other compounds that could have interfered with the CDEF demonstration. Extraction rates were controlled manually by commercial brass valves at a central sample and control table. Injection rates were also controlled manually using the same brass valves. The goal was to extract a combined total of about 5 gpm. During the I/E test, flow rates decreased due to clogging of the injection wells as a result of iron precipitation. Attempts failed to increase the injection flow rates by adjusting flow rates and pressurizing the injection wells. The flow rates, as shown for example, in well I1 (see Figure 4.5), decreased to about 0.2 gpm at the end of the I/E test. At this point, the wells required extensive rehabilitation.

Much more consistent flow rates were maintained during the following push-pull test on wells E6, E3 and I1. The average combined flow rates ranged from 3.4 gpm to 4.0 gpm during this part of the demonstration. Figure 4.6 shows the observed flow rates at each well and the corresponding water tables elevations relative to the ground surface.

The above ground treatment system was operated continuously during injection and extraction of the flushing solution. It was used to treat recycled effluent that was not directly discharged into the storm drain in between tests. The UF system for CD reconcentration was also run in between tests because the limited treatment capacity of the UF (ca. 0.5 gpm) did not permit in-line operation during the injection/extraction periods.

No DNAPL was encountered during the entire demonstration.

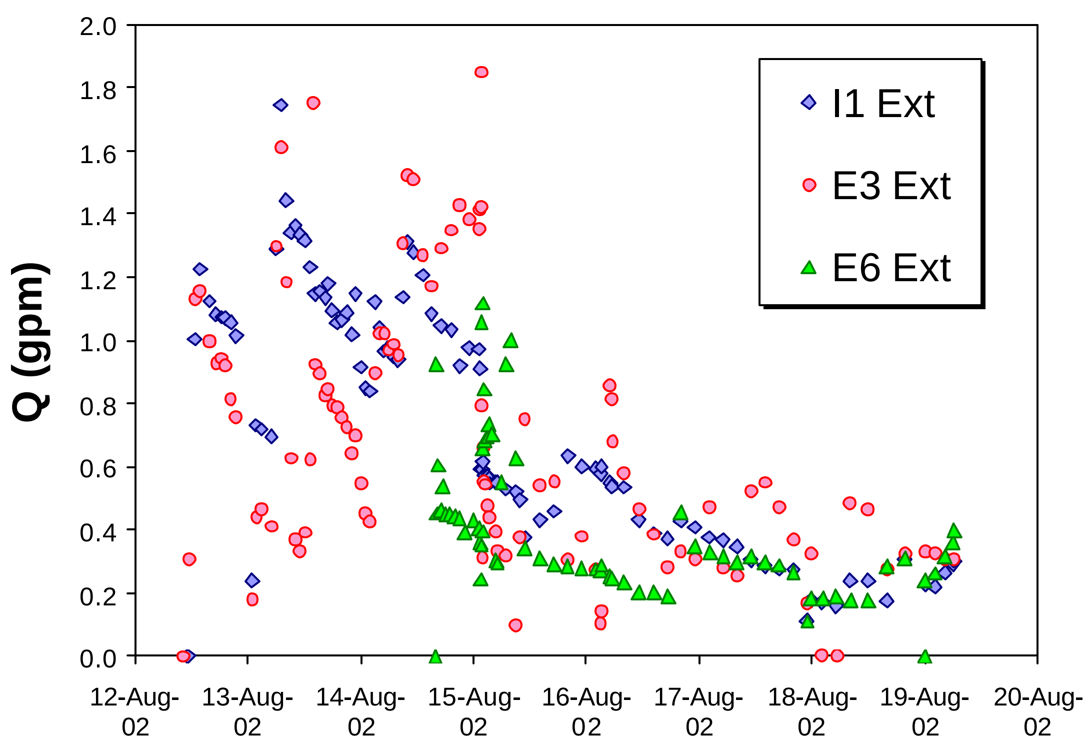



**Figure 4.5:** Flow rates of extraction wells during I/E test.

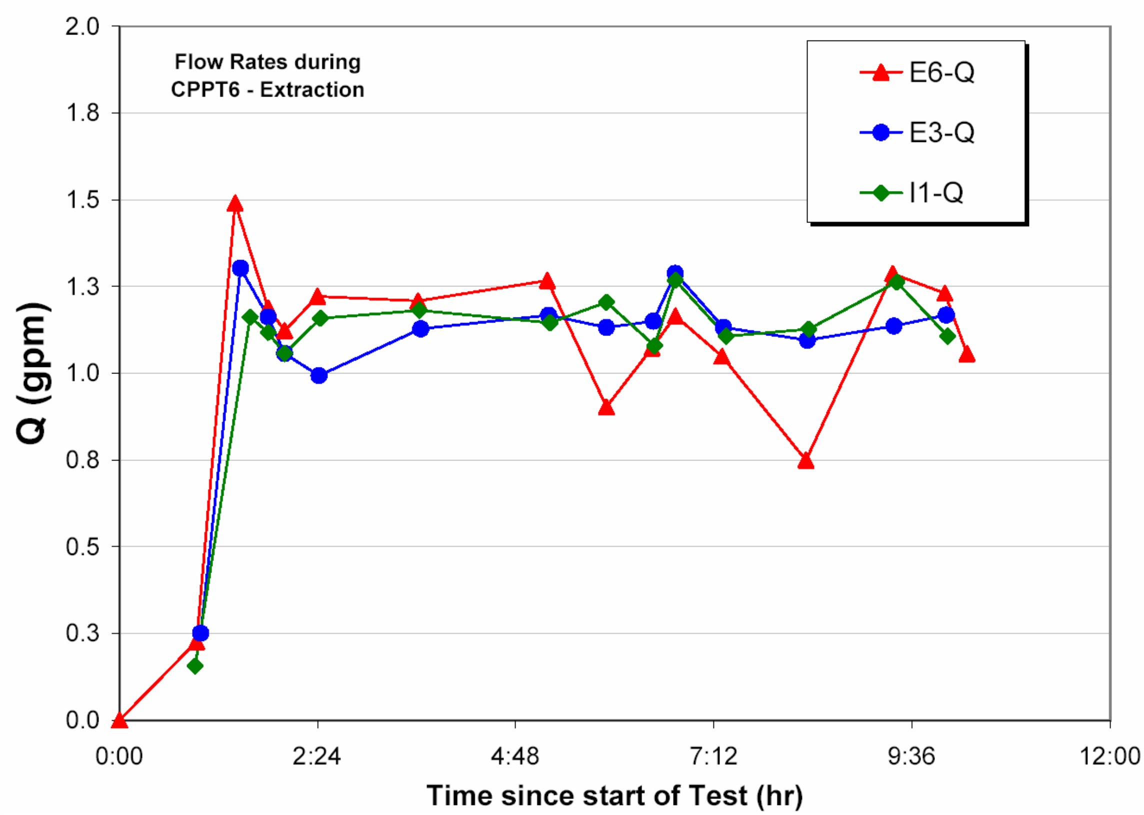



**Figure 4.6:** Flow rates of all three extraction wells operated during CPPT-6.

### 4.4 Amount/Treatment Rate of Material to be Treated

During the seven weeks of CDEF operation, 92,830 liters of CD solution were injected and 109,560 liters were extracted. The sweep volume was equivalent of 11.8 PV. The sweep pore volume for the injection/extraction (I/E) test was calculated based on the screen length of the wells (1.5 m, assuming flow of the flushing solution parallel to bottom of aquifer), multiplied by the area above the source zone (ca. 16 $m^2$) and times the porosity of the treatment zone (31%). The volume obtained was then increased by 25% to account for uncertainties. The resulting sweep volume was 9.3 $m^3$. Based on an estimated bulk soil density of 1.7 tons/$m^3$, the soil weight was about 22 metric tons. The total mass of CD injected was 6,932 kg of which 1,699 kg were injected during the line-drive CDEF, while the remainder was applied during push-pull CDEF and preceding tests. This includes about 2,000 kg of recycled CD of which about 200 kg were recovered CD from the UF system. The remainder was recovered during the I/E tests.

During the pre-PTT, 237,387 liters were extracted and discharged into the storm drain. Another 220,601 liters were extracted and discharged during the post-PTT. The amount of water extracted during both PTT was about 43% less than planned due to sustainable pumping rates, time constraints, and Virginia Water Quality Standards (9 VAC 25-260-5 et seq.). About 129,000 liters were extracted for mixing and dilution of CD stock solution, testing the PVP, air stripper, and UF system, during well rehabilitation, and for hydraulic control of the flushing solution. During the entire demonstration period, 679,526 liters were extracted from Site 11. The treatment system was designed to treat up to 75.6 $m^3$ per day (20,000 gpd), but maximum treatment rates during the demonstration were closer 24.5 $m^3$ (6,500 gpd). The difference between design capacity and realized capacity was mainly due to the smaller than planned treatment zone and was limited by effluent discharge provisions set fourth by VADEQ (see Section 4.4).

### 4.5 Residuals Handling

The demonstration plan (see Appendix I) provided that the extracted and treated solution during would be injected into NABLC's sewage water treatment conveyance system. As stated in Section 4.2., the local POTW withdrew permission to discharge treated effluent to their POTW. Instead, treated effluent was discharged to the stormwater conveyance system. The Virginia Water Quality Standards (9 VAC 25-260-5 et seq.) required that no water from Site 11 was to be discharged into the storm drain before a detailed chemical analysis (Total VOC (32 parameters) and dissolved copper) demonstrated that the effluent met the discharger criteria set by VADEQ. These confirmatory samples were analyzed by an independent laboratory (Reid & Associated, Newport News, VA). The turnaround time of these samples was 24 hr during workdays and up to 3 days on weekends. Obtaining laboratory confirmation for compliance with water quality standards for every change of effluent slowed down the progress of the demonstration and made continued operation of the injection/extraction system much more difficult than initially scoped. In a full-scale implementation, discharge sampling would not be as stringent as this technology demonstration.

Two 55 gal drums containing liquid waste (mainly lubrication oil and other not directly CDEF related hazardous wastes) that could not be treated on-site ware disposed off as hazardous waste by NABLC. Another 13 drums of contaminated soil produced during well drilling were also disposed off by NABLC.

### 4.6 Sampling Plan

The sampling plan developed for this demonstration specified the number of sampling locations, frequency, methodology, chemical analyses, and reporting procedures to be used during the demonstration. The objective was to sample frequently enough to define recovery curves during each phase of operation.

The CDEF monitoring plan included regular sampling and analysis of the target contaminants (TCE., 1,1,1-TCA, 1,1-DCE, and chloroform), the CD flushing solution, and tracers used during the pre-PTT and post-PTT. In addition, the field parameter pH, dissolved oxygen, electric conductivity, and water temperature were recorded. The sampling and monitoring procedures were in accordance with the sampling and monitoring provisions laid out in the demonstration plan (see Appendix I).

Performance sampling for this demonstration was separated into pre-demonstration operation (pre-PTT), CDEF technology demonstration operation, and post-demonstration operation (post-PTT). In addition, a long-term sampling effort to investigate the fate of the left-behind CD began after conclusion of the demonstration (anticipated end date: early fall 2003). The matrix sampled was groundwater. Performance sampling locations are shown in Figure 4.3. The sampling frequency for each period is provided below. The sampling schedule and QA/QC requirements for the demonstration are summarized in Table 4.6. It should be noted that during the CDEF demonstration, many more samples were collected for performance assessment purposes than necessary during a "regular" CDEF remediation.

| Sample Matrix | Analysis | Method | Field Samples | | | Quality Assurance Samples | | |
|---|---|---|---|---|---|---|---|---|
| | | | Number of Locations | Samples per Location | Total per day | Duplicates | Trip Blanks | Total |
| GW | Target VOCs | GC | 8 | 1 / 6hr | 24 | 10% of total field number | 1 per cooler | 2 to 4 |
| GW | CD | TOC Analyzer | 8 | 1 / 6hr | 24 | 10% of total field number | 1 per cooler | 2 to 4 |
| GW | Tracers | GC | 8 | 1 / 6hr | 24 | 10% of total field number | 1 per cooler | 2 to 4 |

**Table 4.6:** Daily sample summary as specified in the demonstration plan. Actual sampling frequency was generally higher compared to a typical CDEF remediation.

The principal sampling locations included (see Figure 3.4):

- Extraction wells
- Injection wells
- Effluent discharge point
- Monitoring wells located in the vicinity of the demonstration site (see Figure 3.14)
- Influent and effluent of the aboveground treatment system

Each sample location was clearly marked and had a dedicated sample port. Additional samples were collected from the off-gas line of the air stripper and between and after the air-activated carbon filter. These gas samples served only as monitors for the loading status as the activated carbon filters and for monitoring of the ambient air quality. These air samples were not used for mass balancing. All aqueous samples were stored in an on-site refrigerator until express-shipped in coolers to the University of Arizona laboratory.

The filed data together with other relevant observations (e.g. weather conditions) were recorded on a specially designed sampling form and, ultimately, transferred to the project database (EXCEL).

Samples were collected from extraction and injection wells (wells E1 through E7 and I1). Samples were also collected regularly from monitoring wells (MW) LS11-MW01T, LS11-MW02S, LS11-MW03T, LS11-MW04, and LS11-MW05D&S. All samples were analyzed for concentrations of CD, VOC, tracer (if present), and field parameter. Only the extraction well data were used to develop mass balance estimates for NAPL mass removal and cyclodextrin mass recovery. The MW samples were used to track movement and fate of the injected CD solution and solubilized NAPL constituents. More specific information regarding the sample collection process can be reviewed in Appendix 1: Demonstration Plan. The depth to the water table was another frequently monitored field parameter. For this, water table depth soundings were recorded at Site 11 wells. The monitoring of MW locations occurred about once a week. The demonstration well field was monitored more frequently.

Samples for performance assessment of the aboveground treatment system were collected at the following locations:

| | |
|---|---|
| Air-Stripper: | Inlet (before treatment) and outlet (after air-stripping); |
| PVP: | Inlet (before treatment), outlet (retentate), and permeate (=contaminant rich phase) |
| UF: | Continuous mode: Inlet and outlet, Batch mode: internal storage tank |

The following parameters were monitored in the UF system:

1) Cyclodextrin concentration in the feed. VOC concentration of selected samples
2) Cyclodextrin concentration in the permeate (filtrate). VOC concentration of selected samples
3) Cyclodextrin concentration in the rejectate. VOC concentration of selected samples
4) Feed and permeate flowrate.
5) Transmembrane pressure and temperature.

For the UF unit, the permeate stream is the solution that passed through the membrane which is the cyclodextrin-depleted stream. The rejectate, on the other hand, corresponds to the cyclodextrin-enriched stream.

The strategy for testing the PVP was similar to the UF system, except that the emphasis of these tests was on the VOC removal. The principal variables that were evaluated included:

1) VOC concentration in the feed. CD concentration of selected samples.
2) VOC concentration in the permeate. CD concentration of selected samples.
3) VOC concentration in the rejectate. CD concentration of selected samples.
4) Feed, permeate and rejetate flowrates.
5) Internal operating parameters of the pervaporation unit such as temperatures, pressures and flowrates.

For the PVP, the permeate stream corresponds to the VOC-enriched stream, while the rejectate corresponds to the VOC-depleted stream. The permeate stream leaving the PVP had a high VOC content (e.g. TCE close to aqueous solubility, 1100 mg/l). This permeate was collected in a 250 gal tank for treatment with the air stripper during CDEF down time. Once the extracted water had passed the PVP (where the VOC were removed) and the UF unit (where the CD was recovered), the VOCs concentration was determined. The UF permeate was discharged when it met all discharge requirements. Otherwise, it was recirculated and treated again using the air stripper.

### 4.7 Analytical Procedures

The analytical procedures, including QA/QC requirements, were followed as outlined in the demonstration plan (see Appendix I). Table 4.7 summarizes the analytical methods used for this demonstration.

| Analyte Type | Matrix | Method Name | Container Type | Container Size | Preservative | Location of Analysis |
|---|---|---|---|---|---|---|
| Target VOCs | GW | GC/FID | glass | 22 ml | None | Field & UA |
| CD | GW | TOC & RF | glass | 20 ml | None | Field |
| Tracers | GW | GC/FID | glass | 22 ml per set of tracers | None | $Br^-$: Field<br>Alc/F/D: UA |
| Confirmatory Samples | GW | GC-MS | glass | 40 ml | Yes | Reed & Assoc. |

**Table 4.7:** Analytical Methodology Summary. UA: University of Arizona, Alc: alcohol tracer (PTT), F: fluorescein, D: deuterium, $Br^-$: bromide. TOC: Total organic carbon analyzer.

The VOC analytical methods used in the University of Arizona laboratory were similar to standard EPA methods, but were adapted for the presence of CD in the aqueous phase. Confirmatory samples for effluent discharge were sent to a local laboratory (Reed&Assoc., Newport News, VA). During the pre-PTT and the first few days of CDEF, VOC were also analyzed in the field using a portable GC. Once CD solution was present in the water samples, i.e. after the first CD injection/extraction tests, the field GC regularly underestimated the actual TCE concentrations determined in both laboratories (UA and Reed&Assoc.). The discrepancy between field GC results and laboratory results was caused by the presence of the CD. Because it was not feasible to implement a purge-and-trap based field GC method, all samples collected during subsequent CDEF and PTT test were sent to the laboratory at UA. CD concentrations were analyzed on-site using a TOC and later verified in the URI lab against a fluorescence spectrometer (TNS method). For further details regarding the analytical procedures see Appendix I: Demonstration Plan.

The alcohol tracer suite for the Pre-PTT included: 2-methyl-1-butanol, 2-ethyl-1-butanol, 2,4-dimethyl-3-pentanol, 2-ethyl-1-hexanol, hexanol, heptanol and the conservative tracer potassium bromide Helium gas was also included and tested as an possible alternative to the alcohol tracers. The Post-PTT tracer suite included: 2-methyl-1-butanol, 4-methyl-2-pentanol, 2-ethyl-1-hexanol, heptanol, and the conservative tracer potassium bromide, deuterium, and fluoescein. During the post-PTT, Neon gas was used instead of helium to account for the lower DNAPL saturation after CDEF.

During the pre-PTT and the first days of CDEF, the compound 1,1-DCE was detectable in wells E3, E6, and I1 at concentration up to 13 mg/L. Later, much higher DCE concentrations were measured (up to 691 mg/L during CPPT6 in well E6). 1,1-DCE is a potential degradation product of 1,1,1-TCA, but the high 1,1-DCE concentrations measured during later stages of the demonstration appeared unusually high. To verify these readings, a set of 10 duplicate samples were taken to an independent laboratory (*Transwest*, Phoenix, AZ) and analyzed using GC-MS and standard EPA methods. The peak that signaled 1,1-DCE in the GC-FID spectrum also appeared in the GC-MS spectrum. The analysis of the GC-MS spectrum revealed that the 1,1-DCE peak could have been caused either by 1,1-DCE or by a some unidentified compounds. Because it may be possible that the decay of CD produced the interfering compound(-s) - although this has not been observed during previous field studies - it was decided to exclude any 1,1-DCE that were higher than those during the pre-PTT (when no CD was present). For the mass balance/DNAPL recovery calculations, it was assumed that DCE concentration remained at the pre-PTT level (average: 4.4 mg/L). This assumption underestimates the actual, but unknown 1,1-DCE concentration during CDEF. This conservative approach however, results in an underestimation of CDEF performance.

# Section 5: Performance Assessment

## 5.1 Introduction

This section provides a summary and assessment of the results from the CDEF demonstration. It is divided into separate discussion of the I/E, CPPT, and aboveground treatment operations. Prior to the performance assessment of CDEF, a detailed summary of the pre- and post-PTT tests results is provided.

The principal data sets used for evaluating the performance of the various aspects of the CDEF demonstration were the aqueous VOC and cyclodextrin concentrations determined at the various sampling locations as well as the feed and flow rate measurements. Non-critical data sets were water temperature, DO, pH, EC, and TCE concentration in the vapor phase, soil hydraulic conductivity and particle size distribution.

## 5.2 DNAPL Mass Removal Assessment with PTT

The partitioning tracer test (PTT) method is currently considered one of the most reliable methods for quantifying subsurface NAPL saturation (e.g., Cain et al., 2000; and Meinardus et al., 2002). The primary advantage of PTTs is that they directly measure a relatively large volume of the subsurface. Therefore the uncertainty caused by the significant data interpolation required for traditional soil-core analysis is essentially eliminated. The PTT can be particularly useful as remediation metrics for NAPL-zone treatment efforts since the same subsurface volume can be directly measured before and after remediation activity. Because of these advantages of the PTT method, two PTTs were conducted at the demonstration site: one PTT before (Pre-PTT) and one after (Post PTT) the CDEF demonstration. The results of the PTT served as a measure of the DNAPL mass removal performance of the CDEF technology. For details regarding the theory of the PTT method and tracer selection process, refer to Appendix V. The following paragraphs describe the PTT design process and provide specifics about the PTT tests.

The tracer sweep efficiency through the target zone was optimized with a series of PTT models that were constructed using a step-wise modeling approach. Initially, an analytical solution for solute transport between a single injection/extraction well pair was used to provide preliminary estimates of appropriate well spacing, tracer pulse volumes, and injection/extraction rates (Figure 5.1). These models also provided a basis for the anticipated degree of hydraulically-related tracer tailing, tracer peak concentrations, and the test duration necessary to capture a significant portion of the tail region. These analytical models provided initial information used to construct a more complex numerical model. Specifically, the analytical models suggested that the target zone could efficiently measured with a series of 3 to 6 injection and extraction wells located between 1.5 m to 3.3 m (5 to 10 feet) apart, a tracer pulse volume of 5,800 liter to 9,500 liter (1,500 to 2,500 gallons), and a test duration of 7 to 10 days.

The numerical flow and transport model TOUGH/T2VOC was then used initially to guide well installation efforts by identifying specific optimal well configurations and locations. The actual well locations are shown in Figure 5.3, and were based on both the results of the preliminary numerical modeling and field observations, including observed lithology and contaminant field-screening results. Generally, well I1 was designed as a PTT injection well, and wells E2, E3, and E6 were designed as PTT extraction wells. The remaining wells (E1, E4, E5, and E7) were installed to provide additional hydraulic control during the PTTs and CDEF.

After well installation, small-scale spatial variations in hydraulic conductivity were characterized with slug tests (see section 4), and these data were then incorporated into the final numerical model. Various PTT simulations were run to identify well injection and extraction rates that optimized hydraulic control, tracer mass recovery, peak concentrations, tracer pulse length, and test duration. Initially, the actual injection and extraction rates for the Pre-PTT were consistent with the model rates. However, some of the wells were unable to sustain these initial rates, and treatment of the extracted water at these flows was less efficient than expected; therefore, extraction rates were decreased after 1.7 days.

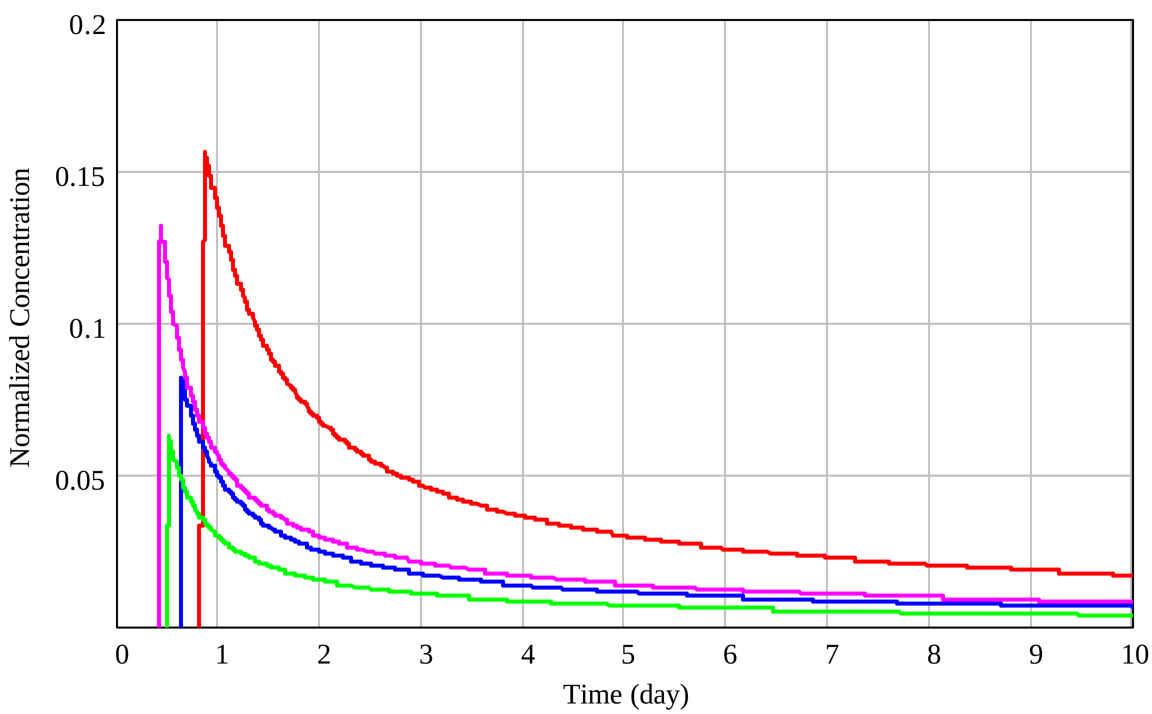



**Figure 5.1**. Example of analytical model results that were used to estimate preliminary well spacing, pumping rates, tracer pulse volume, anticipated peak tracer concentrations, and test duration.

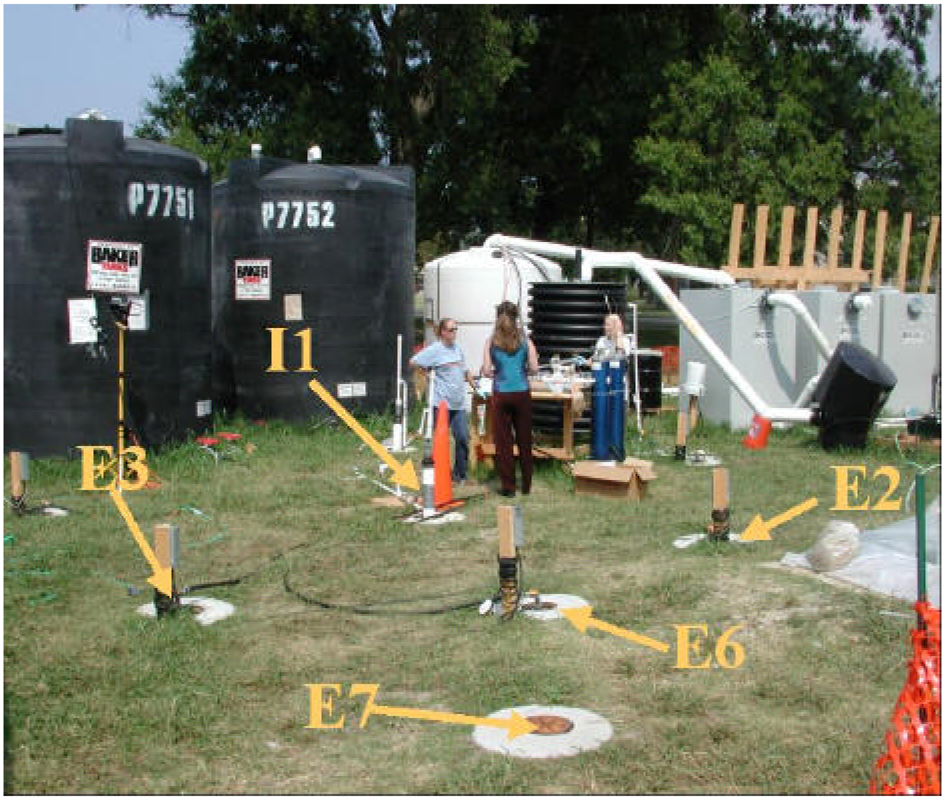



**Figure 5.2.** Site photograph indicating locations of PTT injection and extraction wells.

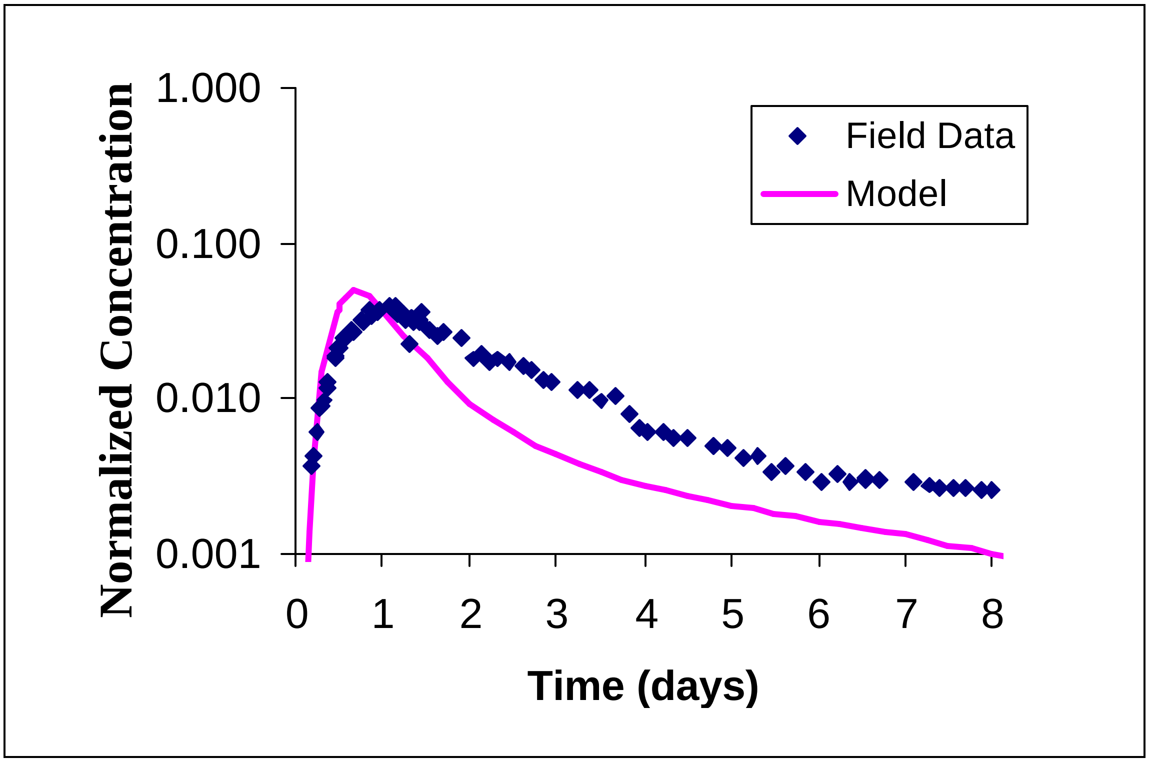



**Figure 5.3.** Comparison of T2VOC-predicted BTC to the bromide BTC observed during the Pre-PTT for well E3.

A comparison of the model-predicted tracer BTC to the observed bromide BTC for the Pre-PTT (well E3) is shown in Figure 5.3. Note the reasonable agreement between the model and the observed concentrations for the initial breakthrough time and the peak concentrations. Higher-than-predicted tracer tailing was observed in the field, and this is at least partially related to the lowered flow rates. However, the change in flows occurred only for the Pre-PTT at a distinct time, and flows remained constant throughout the tests otherwise. Since the modification in system hydraulics affected both the conservative and partitioning tracers equally, the estimate of $S_N$ for the actual sweep volume is not affected, and analysis of the BTCs by the method of moments remains a valid method for determining partitioning tracer retardation.

Cumulative injection and extraction volumes for the Pre- and Post-PTTs are shown graphically in Figure 5.4, and the average well flow rates and tracer pulse volumes are summarized in Table 5.1.

**Pre-PTT**

| Well | Flow Rate (LPM) 0 to 1.8 days | 1.8 to 8.0 days | Purpose |
|---|---|---|---|
| I1 | 13.9 until 0.43 day<br>11.8 until 1.8 day | 7.3 | Tracer injection well (8.6 $m^3$, 0.43 day), then clean water injection for hydraulic control |
| E2 | 9.0 | 4.4 | Tracer extraction well |
| E6 | 9.0 | 4.5 | Tracer extraction well |
| E3 | 9.9 | 8.8 | Tracer extraction well |
| E5 | 12.9 | 7.6 | Hydraulic control with clean water injection |

**Post-PTT**

| Well | Flow Rate (LPM) 0 to 1.9 days | 1.9 to 9.2 days | Purpose |
|---|---|---|---|
| I1 | 5.0 | 4.8 | Tracer injection well (7.0 $m^3$, 0.97 day), then clean water injection for hydraulic control |
| E2 | 4.6 | 4.6 | Tracer extraction well |
| E6 | 5.4 | 5.4 | Tracer extraction well |
| E3 | 6.7 | 6.7 | Tracer extraction well |
| E5 | 3.1 | 12.2 | Hydraulic control and treated effluent disposal |
| E1 | 0.0 | 4.5 (*estimated*) | Hydraulic control and treated effluent disposal |

**Table 5.1:** Summary of well injection and extraction rates for the Pre- and Post-PTTs.

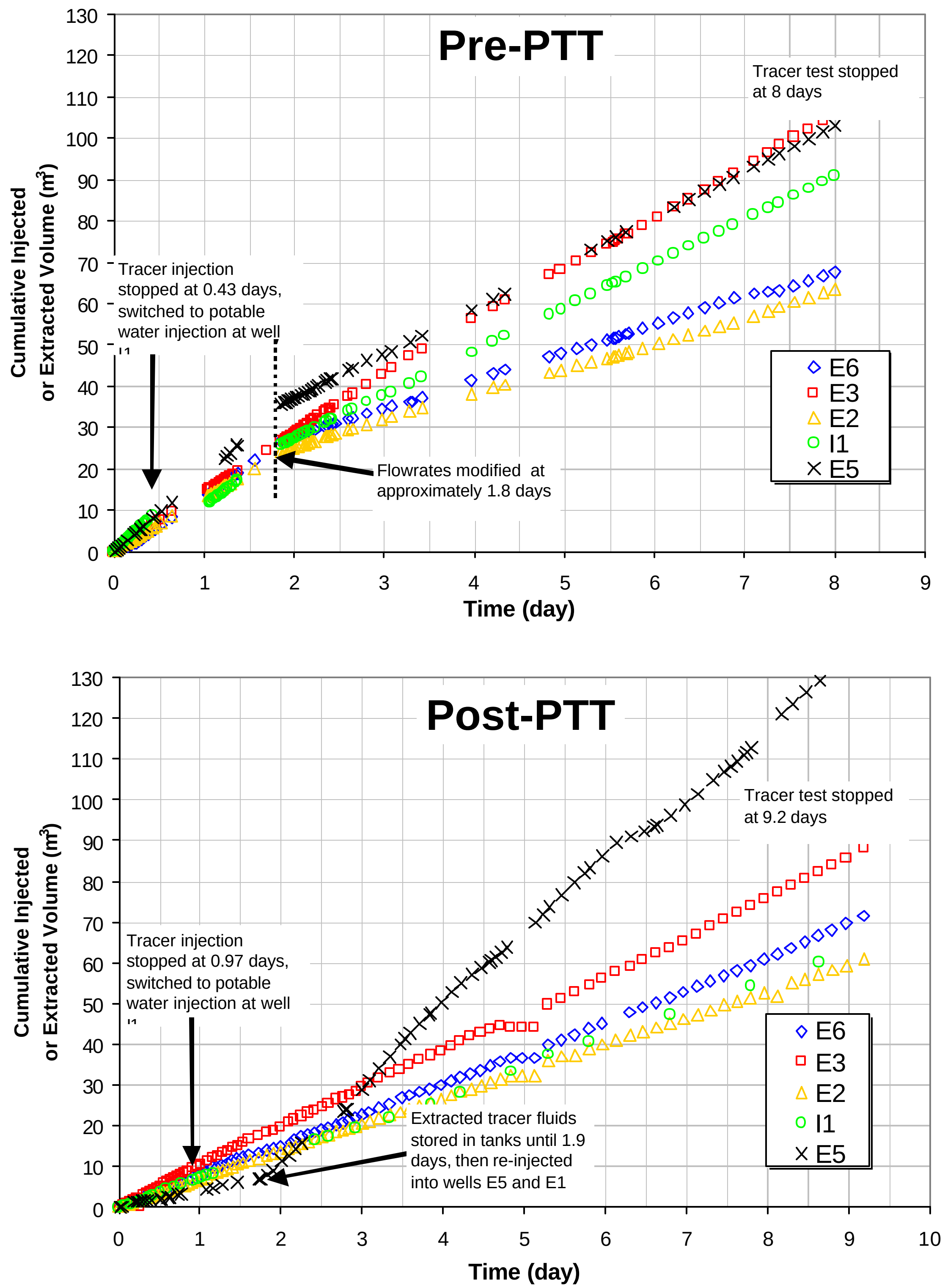



**Figure 5.4.** Cumulative injection and extraction volumes during the PTTs.

A list of the conservative and partitioning tracers used in the PTTs, along with their respective effective $K_{NW}$ values, are included in Table 5.2.

| Pre-PTT | | Post-PTT | |
|---|---|---|---|
| Tracer | $K_{NW}$ | Tracer | Effective $K_{NW}$ |
| Bromide | 0.0 | Bromide | 0.0 |
| Helium | 2.42[a] | Neon | 3.24[a] |
| 2-methyl-1-butanol | 3.71[b] | 2-methyl-1-butanol | 3.38[b] |
| 2-ethyl-1-butanol | 13.4[b] | 4-methyl-2-pentanol | 9.66[b] |
| hexanol | 18.6[d] | 2-ethyl-1-hexanol | 131[b] |
| 2,4-dimethyl-3-pentanol | 71.3[b] | heptanol | 163.1[c] |
| heptanol | 163.1[c] | | |
| 2-ethyl-1-hexanol | 202[a] | | |

Sources

[a]Divine et al. 2003

[b]Dugan et al. 2003

[c]Young et al. 1999

[d]Wang et al. 1998

**Table 5.2.** Tracer suite for the field PTTs with $K_{NW}$ values. Note effective $K_{NW}$ values for Post-PTT partitioning tracers are based on results presented in Dugan et al. (2003).

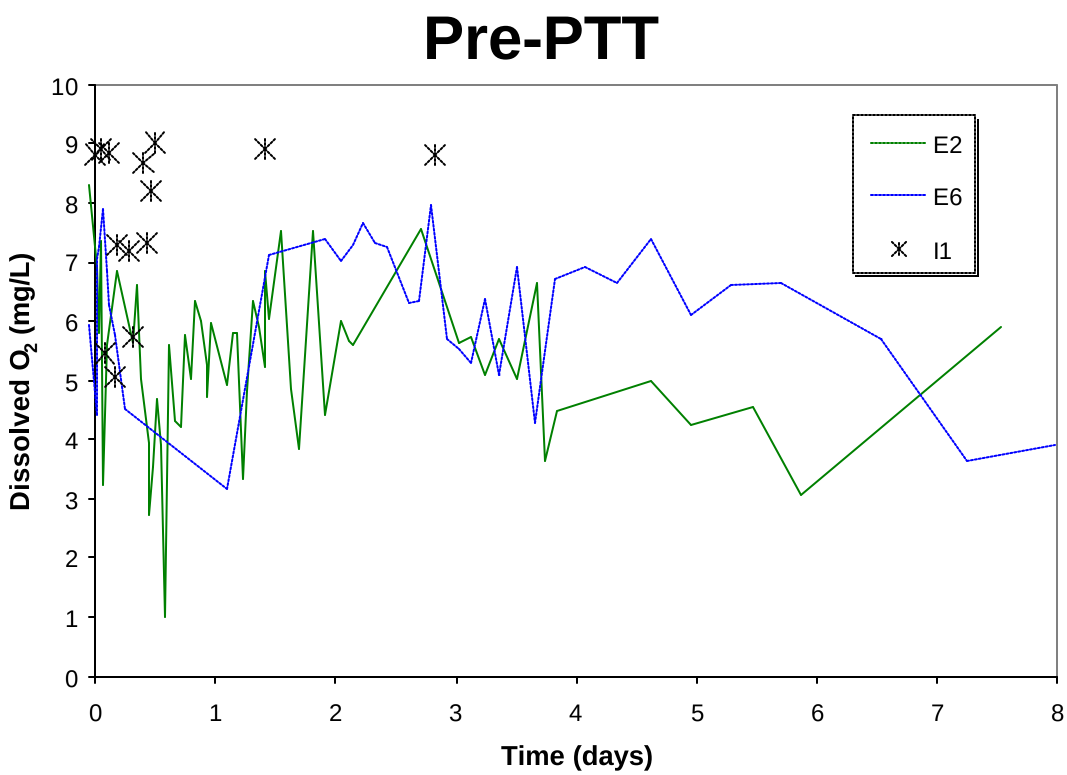
Tracer samples were collected from in-line effluent sampling ports at pre-determined time intervals based on the results of the numerical models. Early in the tests, samples were collected every 30 minutes to ensure accurate characterization of the BTC peak, while late in the tests when the changes in tracer concentrations were small, samples were collected every couple of hours. The sampling frequency was confirmed real-time in the field by observed changes in the specific conductance of extraction fluids.

Samples were analyzed for bromide with an ISE in the field within approximately 2 weeks of collection. Samples collected for alcohol tracers were placed in coolers and shipped to the University of Arizona for analysis (see Appendix 1: Demonstration Plan for a description of the analytical methods). Water samples were analyzed for dissolved helium and neon with a field GC (Shimadzu 8A) by a direct headspace analysis method similar to the method described by Divine (2000).

*Results and Analysis:* For the Pre-PTT, the transport of the alcohol tracers clearly indicates that NAPL was present in the sweep zone. However, the partitioning tracer retardation values relative to bromide were small, indicating the initial average NAPL saturation prior to remediation was relatively low. In fact, the maximum observed retardation for any alcohol tracer during the Pre-PTT was 1.10, which is below the optimal minimal PTT design retardation of 1.2 discussed earlier. For the Post-PTT the average differences in tracer transport were even smaller. Theoretically, $S_N$ can be calculated from very small retardation values; however, the effects of tracer measurement and mass-balance errors become more significant, creating a practical lower $S_N$ quantification limit for the PTT method. The effective value of this lower limit value for these PTT is unknown, as it is dependent on the specific errors and uncertainties associated with multiple factors. However, based on the original PTT design objectives, estimated analytical uncertainties, and the characteristics of the observed BTCs, the lower $S_N$ quantification limit for these PTTs is estimated at approximately 0.5%.

The tracer recoveries for the Pre-PTT ranged from 65-79%, and these values are consistent with the anticipated tracer mass recovery based on the numerical models. During the Post-PTT extraction fluids were reinjected into wells E5 and E1 due to regulatory requirements. The air-stripper treatment system was designed primarily to treat TCE and other VOCs, Consequently, measurable concentrations of bromide and alcohols were present in reinjected water. A second minor tracer peak is observable in all Post-PTTs BTCS caused by fluids injected into well E1 and/or E5. Additionally, the larger primary tracer peak may also mask the effects of reinjected fluids, and this may explain the high tracer mass recoveries calculated for the Post-PTT (110-138%), even when the distinct secondary peaks are ignored. This is supported by the fact that the mass recovery for dissolved neon, which was completely treated by the air-stripper and therefore not present in reinjection fluids, was significantly lower than the alcohol and bromide mass recoveries (discussed further in the following Dissolved Gas Tracers section). While the effects of reinjected fluids introduce error in the PTT analysis, the significant majority of the tracer response is caused by transport and partitioning processes within the target sweep zone; therefore, the analysis of Post-PTT data still provides information on post-remediation $S_N$.

Based on visual observations of the raw tracer BTCs and tracer mass-balance calculations, biodegradation of some alcohol tracers occurred during the PTTs. Furthermore, a significant consumption of dissolved oxygen (indicating aerobic biological activity) was observed between the injection well and the extraction wells. As shown in Figure 5.5, dissolved oxygen consumption across the test region was greater during the Post-PTT. Possibly, this was caused by increased microbial activity induced by remediation efforts and the presence of significant residual cyclodextrin in the sweep zone. Generally, straight-chain alcohols are preferably biodegraded, and this was supported by the field data. Therefore, only BTC data from methylated and ethylated alcohols were utilized for $S_N$ estimation. Additionally, tracers with higher $K_{NW}$ values occasionally yielded inconsistent and unreliable $S_N$ estimates. This response has been observed by others (e.g., Brooks et al., 2002) and is primarily related to the high relative sensitivity of the $S_N$ calculation for high $K_{NW}$ values to mass-balance and temporal moment estimation errors. In these cases, $S_N$ was primarily estimated from tracers with relatively low $K_{NW}$ values (i.e. 3-15).



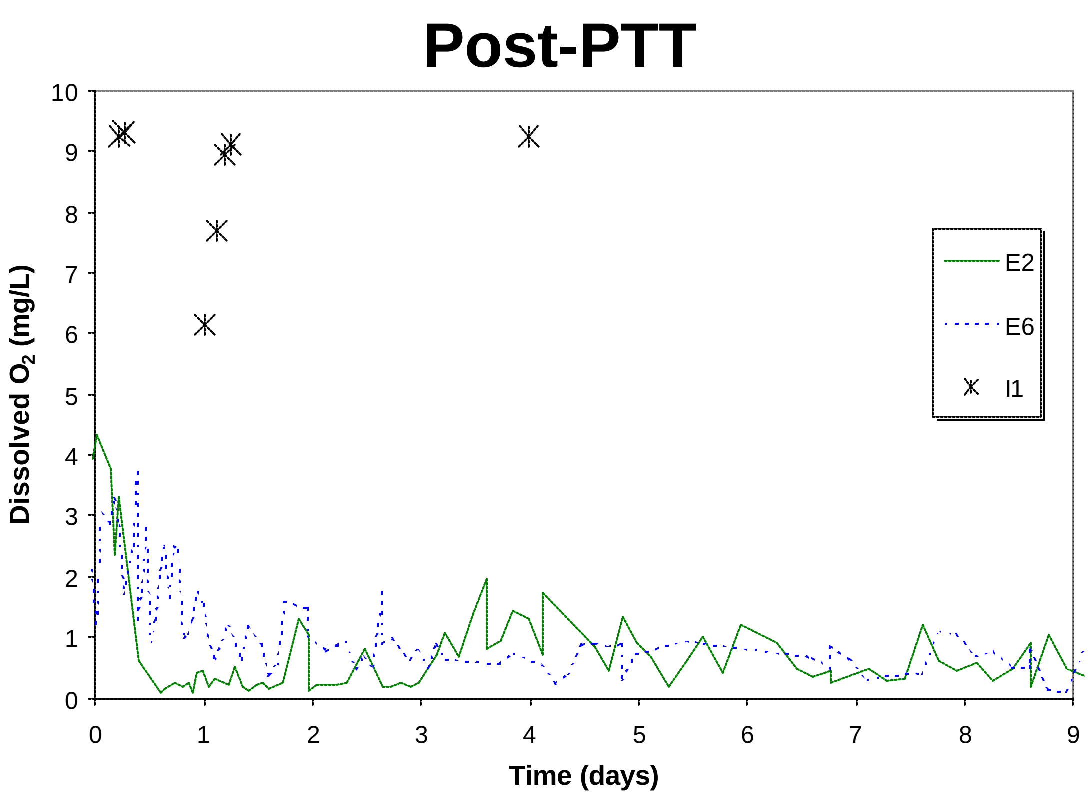




**Figure 5.5:** Dissolved oxygen concentrations during Pre- and Post-PTT. Note that samples for well I1 were collected from the injection fluid immediately prior to entering the well.

For the Pre-PTT, the total sweep volume was 62.4 $m^3$, and the best estimate of average $S_N$ in this zone is 0.67% (the low- and high-end best estimates are 0.29% and 1.04%, respectively). The total sweep volume for the Post-PTT was 54.7 $m^3$, and the best estimate of average $S_N$ in this zone from the Post-PTT data is 0.13%. As indicated earlier, this value below the estimated practical $S_N$ quantification limit of ~0.5%. The data suggests the actual $S_N$ value is likely to be between 0.03% and 0.52%. The results of the $S_N$ estimation from the alcohol data for the Pre- and Post-PTT, including $S_N$ estimated for the sub-zones measure by each extraction well, are summarized in Table 5.3. Tracer BTCs for all extraction wells are presented in Figures 5.6 and 5.7, respectively.

| **Pre-PTT** | | **Post-PTT** | |
|---|---|---|---|
| ***Well E3*** | | | |
| Sweep volume ($m^3$) | 28.1 | Sweep volume ($m^3$) | 25.0 |
| $S_N$ best estimate | 1.42% | $S_N$ best estimate | 0.23% |
| $S_N$ high | 2.20% | $S_N$ high | 0.87% |
| $S_N$ low | 0.65% | $S_N$ low | 0.04% |
| ***Well E2*** | | | |
| Sweep volume ($m^3$) | 17.8 | Sweep volume ($m^3$) | 14.2 |
| $S_N$ best estimate | 0.05% | $S_N$ best estimate | 0.08% |
| $S_N$ high | 0.11% | $S_N$ high | 0.08% |
| $S_N$ low | 0.00% | $S_N$ low | 0.03% |
| ***Well E6*** | | | |
| Sweep volume ($m^3$) | 16.6 | Sweep volume ($m^3$) | 15.4 |
| $S_N$ best estimate | 0.04% | $S_N$ best estimate | 0.03% |
| $S_N$ high | 0.06% | $S_N$ high | 0.14% |
| $S_N$ low | 0.02% | $S_N$ low | 0.02% |
| ***Weighted Averages*** | | | |
| Total sweep volume ($m^3$) | 62.4 | Total sweep volume ($m^3$) | 54.7 |
| $S_N$ best estimate | 0.67% | $S_N$ best estimate | 0.13% |
| $S_N$ high | 1.04% | $S_N$ high | 0.52% |
| $S_N$ low | 0.29% | $S_N$ low | 0.03% |

**Table 5.3.** Summary of $S_N$ estimates for the Pre- and Post-PTTs

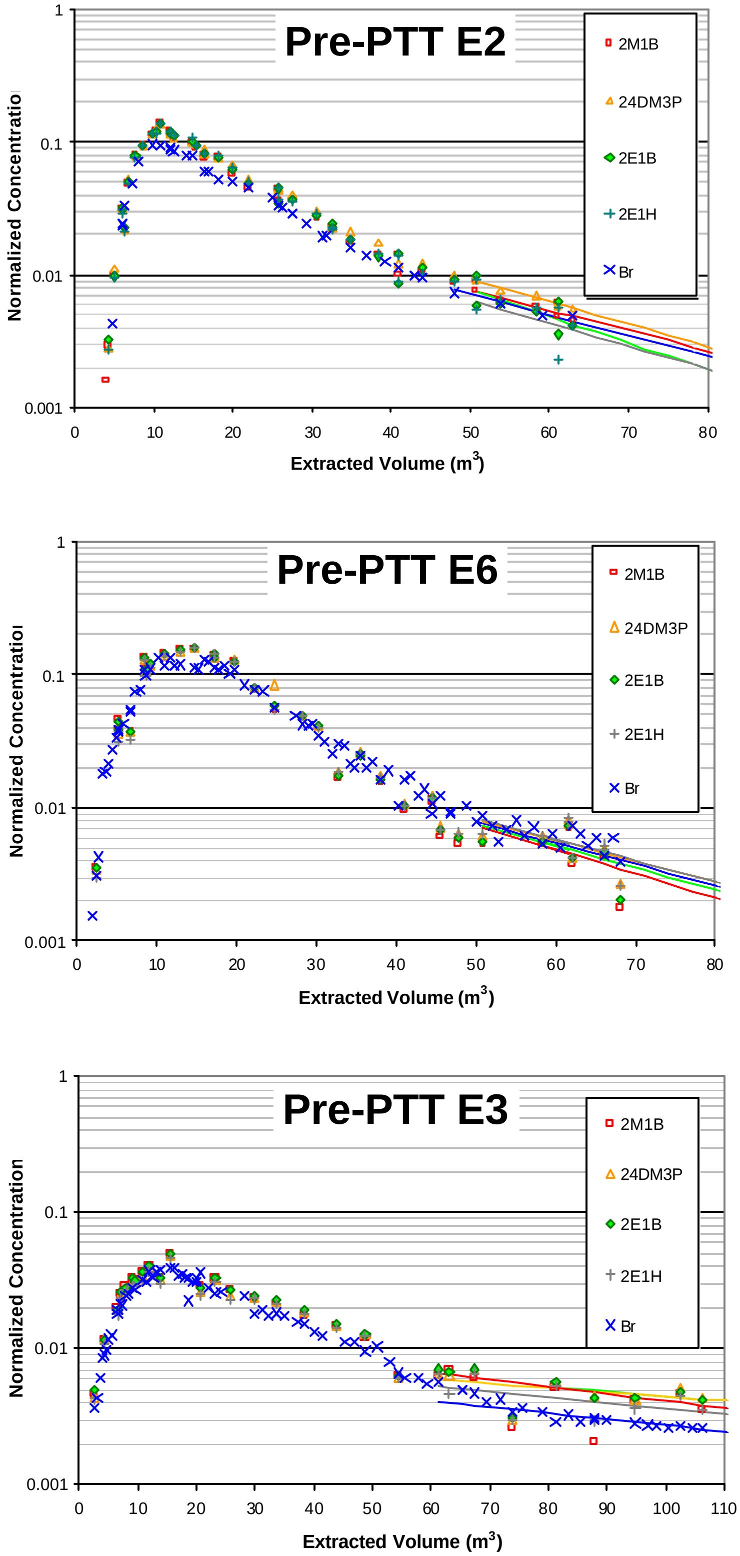



**Figure 5.6.** Pre-PTT tracer BTCs for extraction wells E2 (top), E6 (middle), and E3 (bottom).

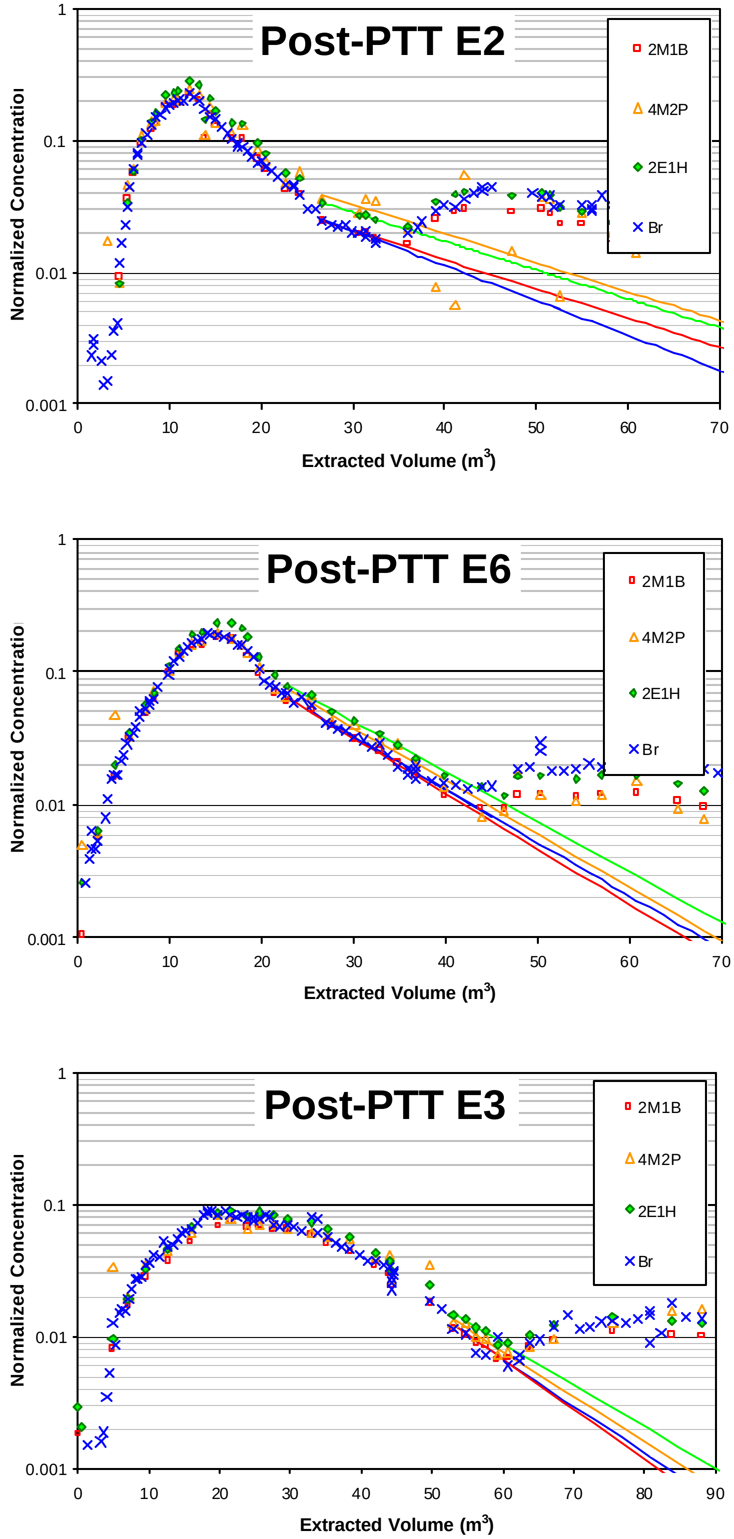



**Figure 5.7.** Post-PTT tracer BTCs for extraction wells E2 (top), E6 (middle), and E3 (bottom).

The amount of contaminant mass removed during the both PTTs was determined from the water samples taken during the tests. Table 5.4 summarizes the mass recovery data.

| Well ID | Sum TCE | Sum 1,1,1-TCA | Sum 1,1-DCE |
|---|---|---|---|
| | g | g | |
| | | | |
| E2-Pre | 1014 | 29 | 277 |
| E2-Post | 541 | 256 | 268 |
| E 6-Pre | 2897 | 2762 | 299 |
| E 6-Post | 3003 | 1505 | 315 |
| E 3-Pre | 5523 | 1164 | 468 |
| E 3-Post | 2323 | 779 | 388 |
| | | | |
| **Pre - Total** | 9434 | 3956 | 1044 |
| **Post - Total** | 5866 | 2540 | 971 |
| | | | |
| **Total (g)** | **15300** | **6496** | **2015** |
| | | | |
| **SUM VOC** | **23811** | **g** | |
| | **17.0** | **liter** | |

**Table 5.4:** Contaminant mass recoveries during both PTTs. The mass of 1,1-DCE is a best estimate based on its average concentration measured during the pre-PTT (see Section 4 for details). For the conversion from mass to volume, the VOC mass was divided by a DNAPL density of 1.4 g/cm$^3$.

Generally, the PTTs indicate that the majority of NAPL was present in the subzone measured by well E3, with lesser amounts in the subzones measured by wells E6 and E2. This observation is consistent with results from field screening during well installation, background contaminant concentration measured at these wells, and probable DNAPL location based on local lithology and the geologic topography of the underlying clay unit. Clearly, the PTTs indicate that $S_N$ decreased after remediation. The weighted average pre-demonstration $S_N$ best estimate was 0.67% versus 0.13% afterwards (see Table 5.3), which equals 81% reduction in DNAPL saturation. The PTT results also showed that the subzone characterized by well E3 was the most contaminated (pre-demonstration $S_N$ = 1.42%). The $S_N$ of this zone decreased to 0.23% after the demonstration, which equals 83.8% reduction in DNAPL saturation.

The total treated contaminant mass was calculated from measured concentrations in demonstration system effluent samples (see following sections). Based on this metric, approximately 30 liters of DNAPL contaminant were removed during all activities at Site 11, including the CDEF and PTTs.

The observed transport of the helium tracer during the pre-PTT suggests that some trapped air was present in the sweep zone. Air may have been introduced during well installation, well development, and slug testing. Due to the low initial $S_N$ and the relatively low $K_{NW}$ value for helium (2.42), even a small amount of trapped air would cause a noticeable affect on the observed BTC. During the remediation activities between the PTTs, all site wells were sporadically pumped at various rates, and the wells were frequently dewatered due to high pumping rates. Additionally, large volumes of remediation fluids were quickly injected into the NAPL-zone wells, and foaming was often observed at injection wells and at sampling ports. Consequently, it is likely a significant amount of air was introduced into the subsurface during remediation activity, and therefore, the retardation of dissolved neon in the Post-PTT was caused by both NAPL- and gas-phase partitioning. This is supported by the increase in estimated average $S_A$ between the Pre- and Post-PTTs (from 0.1% to 0.5%). The partitioning model based on three-phase partitioning (water-NAPL-air) was used to estimate $S_N$ and $S_A$ for both the Pre- and Post-PTTs (see Appendix V).

One unanticipated advantage with the dissolved neon tracer was observed during the Post-PTT. As noted earlier, extracted fluids were re-injected into wells E5 and E1 due to regulatory requirements. The air-stripper treatment system was unable to completely treat the alcohol and bromide tracers, causing secondary BTC peaks and mass-recovery errors. However, the air-stripper completely treated neon; therefore, secondary neon peaks are not present in the BTCs, and the overall mass recovery is lower (Table 4). For example, neon tracer recovery at E6 was 30.0%, while the average alcohol mass recovery was 43.5% and the bromide recovery was 40.4%. The relative neon recovery at well E2 was even lower. Possibly this is caused by the greater effect of re-injection at this well (well E2 may have received proportionally more re-injection fluids from wells E5 and E1 due to its location and test hydraulics).

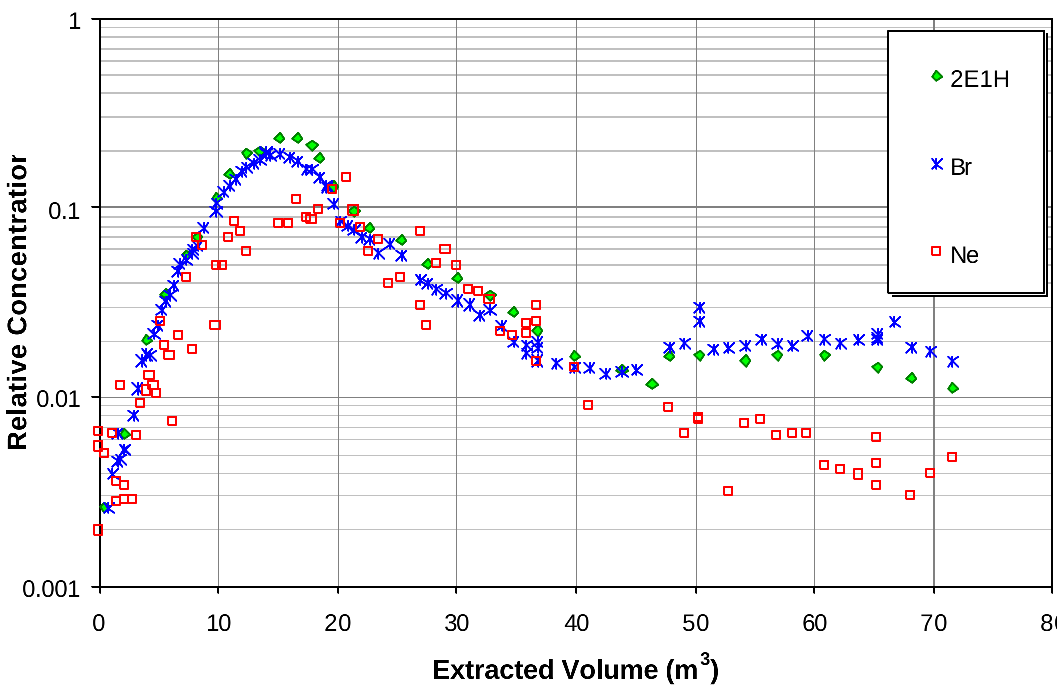



**Figure 5.8.** Post-PTT tracer BTC for E6 showing partitioning tracers: dissolved neon and 2-ethyl-1-hexanol (2E1H); and conservative tracer: bromide.

| | Bromide | Alcohols | Neon |
|---|---|---|---|
| E6 | 40.4% | 43.5% | 30.0% |
| E2 | 38.4% | 43.8% | 12.9% |

**Table 5.5.** Tracer mass recoveries for Post-PTT.

| **Pre-PTT** | | | |
|---|---|---|---|
| Well | Tracer | $S_N$ | $S_A$ |
| E3 | Alcohols | 1.4% | -- |
| E2 | Alcohols | 0.05% | -- |
| E6 | Alcohols | 0.04% | -- |
| | Helium | <0.01% | 0.12% |
| Estimated Sweep Volume Average | | | |
| | | **$S_N$** | **$S_A$** |
| | | **0.7%** | **0.1%** |
| **Post-PTT** | | | |
| Well | Tracer | $S_N$ | $S_A$ |
| E3 | Alcohols | 0.23% | -- |
| E2 | Alcohols | 0.08% | -- |
| | Neon | 0.08% | 0.67% |
| E6 | Alcohols | 0.03% | -- |
| | Neon | 0.03% | 0.29% |
| Estimated Sweep Volume Average | | | |
| | | **$S_N$** | **$S_A$** |
| | | **<0.5%** | **0.5%** |

**Table 5.6.** Summary of $S_N$ and $S_A$ estimates for Pre- and Post-PTTs.

The tracer BTC for neon is compared to the BTCs for bromide and 2-ethyl-1-hexanol (2E1H) in Figure 5.8 (Post-PTT, well E6). One notable observation is that the neon data exhibit significant scatter, or "noise", compared to the other tracers. Both helium and neon have high Henry's Law constant values, and therefore, are highly sensitive to sample collection and preparation errors. Additionally, air in the pumps or extraction fluid transfer lines caused by dewatering and/or turbulent flow can cause tracer mass loss. Based on the observed BTCs and recorded water levels during pumping, this is believed to have occurred for wells E3 (both Pre- and Post-PTT) and E2 (Pre-PTT); therefore, data from these wells were not used to estimate $S_N$ and $S_A$ with the gas tracers. Dissolved gas BTCs for wells E6 (both Pre- and Post-PTT) and E2 (Post-PTT) appeared not to exhibit these critical data errors, although significant noise is present in the data. However, Divine et al. (2003) show by sensitivity analysis that random measurement noise can be largely overcome by a high sampling frequency, as is the case for these BTCs.

Therefore, data for these wells were used to estimate $S_N$ and $S_A$. Table 6 summarizes and compares the results of the PTTs for both the alcohol and dissolved gas tracers.

The pre-PTT results confirm that DNAPL was present in the test zone before remediation, and the post-PTT results indicate that $S_N$ decreased due to remediation activities. The average initial pore-space saturation was low (0.67%). $S_N$ estimates from the various tracer pairs are relatively inconsistent, indicating uncertainty and suggesting that the relatively small amount of DNAPL present was near the reliable quantification level for the tests. Furthermore, this suggests that there is relatively greater uncertainty associated with the post-PTT. The Post-PTT results indicate that $S_N$ decreased. The remaining $S_N$ value was 0.13%. By subtracting the contaminant mass/volume measured in effluent fluids during remediation (~30 liters) from the initial $S_N$ estimated by the Pre-PTT, the demonstration resulted in a reduction of approximately 70% to 81% in DNAPL volume. Based on these results, about 8 liter DNAPL were left behind.

For this project, there is reasonable certainty associated with the estimate of VOC mass removed based on effluent concentrations. In short, the estimated VOC mass removed is believed to be quite accurate; however, the estimates of actual initial and final $S_N$ are associated with relatively high uncertainty due to the low $S_N$ values. We believe the results of these PTTs clearly indicate that further work is needed to better understand practical limitations of the PTT method, particularly for quantifying low $S_N$ values.

## 5.3 CDEF Treatment of Subsurface DNAPL Contamination

The TCE and 1,1,1-TCA concentrations in the extraction well effluent increased significantly during CDEF treatment. Different degrees of contaminant solubility enhancements were observed as the result of variations in the injection and extraction scheme. The following is a summary of the injection/extraction test (I/E, section 5.3.1) and cyclodextrin push-pull tests (CPPT, section 5.3.2).

### 5.3.1 Injection/Extraction Demonstration (I/E)

The injection/extraction tests were carried out using all 8 wells drilled for this demonstration (see Figure 5.9). Wells I1, E2, E3, and E4 served as extraction wells. Well E4 was operated for hydraulic control purposes only during the CD injection period and was then turned off for the remainder of the I/E demonstration. The water extracted from E4 was, after air-stripper treatment, injected into wells E5 and E1 to maintain lateral hydraulic control of the well field. Wells E2, E6 and E7 were used as injection wells. Well E6 was converted into an extraction well after serving as an injection well for about 2 days. A slug of 8,495 liter (2,247 gal) CD solution at an average concentration of 22.8% (wt/wt) was injected over a 24-hr period. The injected volume of CD solution was equivalent to a CD mass of 1,936 kg. The slug volume was approximately one sweep volume. Extraction from well E3 and I1 began immediately after all CD solution was injected. The extracted water, after treatment, was reinjected into wells E2, E7, and temporarily into E6. Over a period of seven days, 54,117 liters were extracted from the subsurface, while 62,757 liters were injected. Another 12,394 liter of groundwater were extracted and reinjected for hydraulic control purposes. The processed flushing solution volume (not counting the water extracted for hydraulic control of the well field) was equal to about 6.7 PV, which means that about 0.96 PV was flushed per days. The total mass of CD recovered during the test was 1,525 kg, or 79% of the injected CD mass. Table 5.7 summarizes the test conditions during the injection/extraction test.

Initial extraction rates ranged between 1.2 gpm and 1.5 gpm per well. Lateral hydraulic control was achieved by extracting from well E4 during the CD injection and injecting the E4 water, supplemented with tap water, into wells E5 and E1. The goal was to extract a combined total of approximately 5 gpm. During the test, flow rates decreased due to clogging of the injection wells. Attempts failed to increase the injection flow rates by adjusting flow rates and pressurizing the injection wells. The flow rates, as shown in Figure 5.10, decreased to about 0.2 gpm at the end of the test.

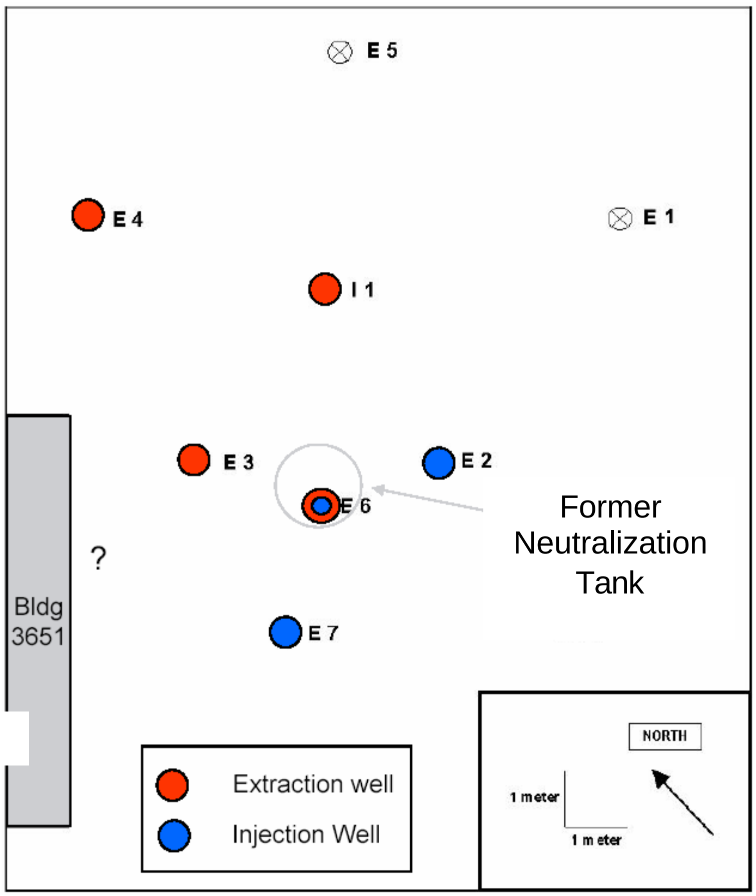



**Figure 5.9:** Injection and extraction well set up used during the I/E demonstration. Note that well E6 served initially as an injection well, but was converted to an extraction well during the test. Well E4 was operated only during injection of the CD solution to maintain hydraulic control (i.e. pull the flushing solution towards extraction wells). Tap water was injected into well E1 and E5 for hydraulic control purposes.

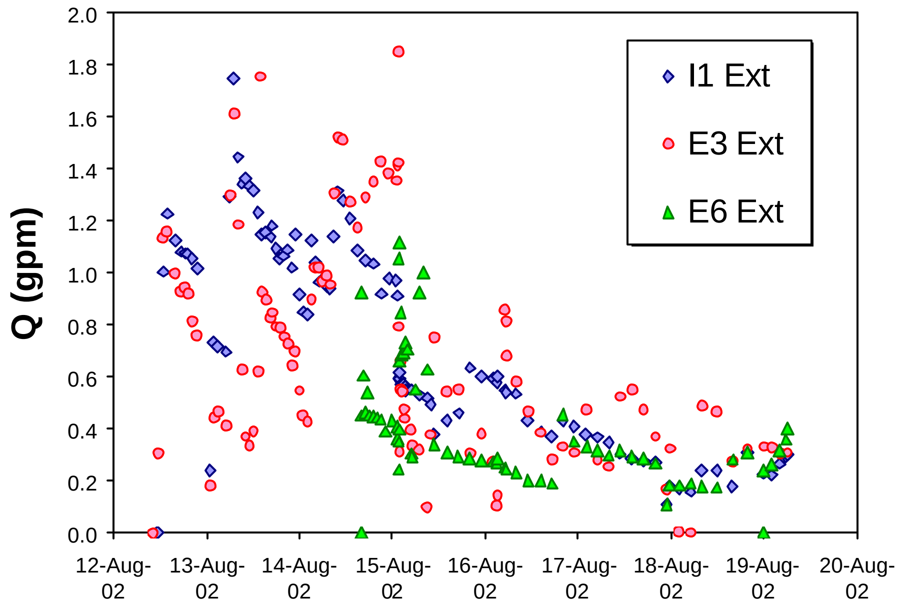



**Figure 5.10:** Flow rates of extraction wells during I/E test.

The clogging of the injection wells was due to iron precipitation. It was the principal reason why the I/E test had to be terminated and why the CDEF injection/extraction scheme had to be modified. The well clogging was never encountered in previous field studies and was not considered in the demonstration test design either. Therefore, no provisions were in place to remediate the precipitation problem in the field. The iron precipitation was caused by aerating the anaerobic flushing solution in the air stripper. While some of the iron precipitated inside the air stripper, a fraction was transported into the injection wells were it cloaked the well screen. Furthermore, the water leaving the air stripper was near DO saturation. When it mixed with the groundwater after injection, it caused additional precipitation within or near the wells. Iron precipitation could have been prevented if the injectate had remained anaerobic. This would have required retrofiting the air stripper to run under anaerobic conditions, for example, by stripping under a nitrogen atmosphere. Because of time constraints, a retrofit was not possible. Also, the damaged PVP could not substitute for the air stripper as the principal means of treating the effluent in continuous mode. During PVP treatment, the wastewater remained anaerobic and it is likely that the well clogging could have been prevented if the PVP had been fully functional.

The injected 22.8% CD slug had a pH 6.6 at 25.1 $^{0}$C. The electrical conductivity was at 3.729 mS and the dissolved oxygen saturation was 94.2%. Prior to the I/E test, the average water temperature in the extraction wells ranged from 21.4 $^{0}$C to 24.8 $^{0}$C. The pH ranged from 6.3 to 6.6 and the electrical conductivity ranged from 0.199 mS to 0.394 mS. The dissolved oxygen (DO) levels, as determined during the pre-PTT, ranged from 6.0 mg/L to 8.8 mg/L (or 79% to 100% saturation). During the I/E test, the DO levels dropped below 5% after breakthrough of the CD flushing solution. The pH and temperature remained essentially unchanged, while the EC increased up to 1.59 mS during CD breakthrough.

| Well ID | Vol injected | Vol extracted | Duration injection | Duration extraction | Mass CD injected | Mass CD extracted |
|---|---|---|---|---|---|---|
| | liter | liter | min | min | kg | kg |
| | | | | | | |
| I1 | | 23321 | | 9766 | | 475 |
| E 2 - CD | 2492 | | 1387 | | 568 | |
| E 2 | 21414 | | 9767 | | | |
| E 3 | | 21401 | | 9831 | | 671 |
| E 6 - CD | 2971 | | 1420 | | 677 | |
| E 6 | 6137 | 9395 | 3100 | 6612 | | 379 |
| E 7 - CD | 3031 | | 1370 | | 691 | |
| E 7 | 26711 | | 9767 | | | |
| E 4 | 12394 | | | | | |
| E1/E5 | | 12394 | | | | |
| **Total** | **75151** | **66511** | | | **1937** | **1525** |

**Table 5.7:** Summary of test conditions during the I/E demonstration at Site 11. The average CD concentration injected into wells E2, E6 and E7 was 22.8% or the equivalent of 1,936 kg of CD. Wells E1, E4, and E5 served as hydraulic control wells. Well E6 was converted to an extraction well about 2 days into the test.

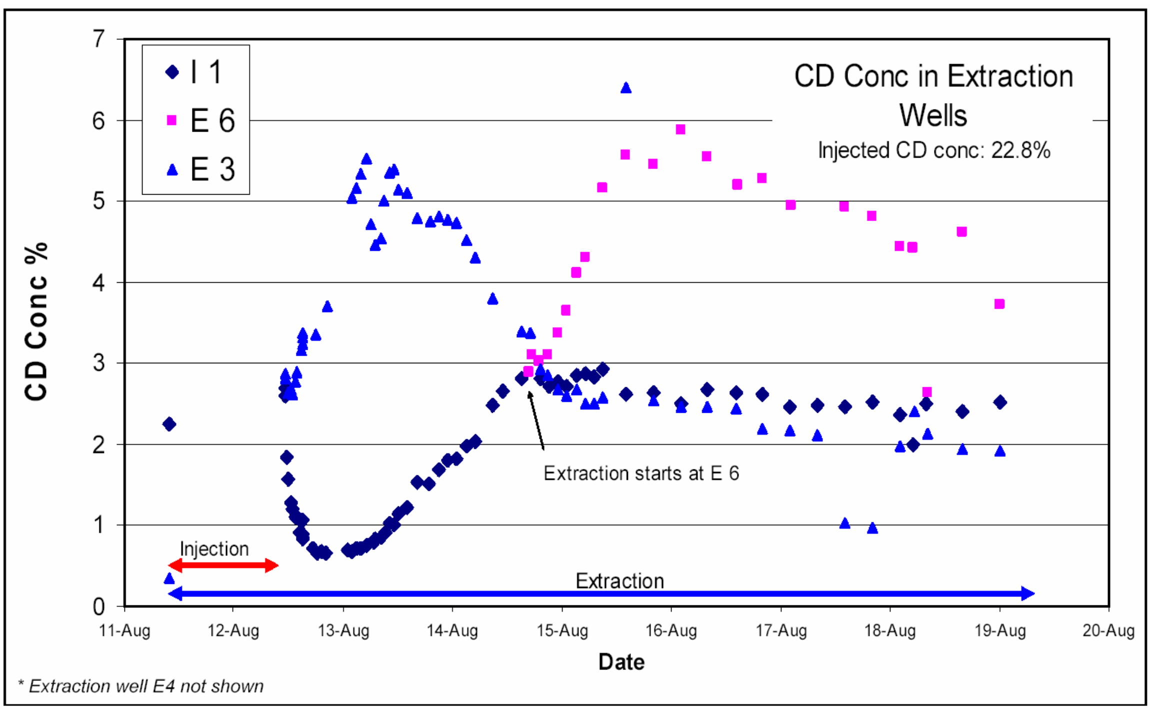



**Figure 5.11:** History of CD concentrations in the extraction wells I1, E3, and E6.

The history of the CD concentrations measured during I/E is summarized in Figures 5.11 through 5.13. These figures show that the extraction wells responded uniquely to the CD injection. The presence of CD in well E3 was detected immediately after extraction began (Figure 5.12). At this time, the CD concentration was already at 2.6% (or: 11.4% of the injected CD slug). The CD concentration increased steadily until it peaked at about 5.6% approximately 23 hours after extraction began. This CD peak concentration is about ¼ of the injection concentration and equals a dilution factor of 4.1. The performance criterion of CD concentration at the extraction well was 5% to 10% (see Section 4). The observed 5.6% peak concentration fell within this range. The CD concentration decreased to about 2.7% within the following 36 hours and reached about 2% at the end of the test. The total mass of CD recovered from well E3 was 671 kg (see Table 5.7). There was a noticeable change in the recovery rate after 2.5 days of flushing. Of the total mass recovered at E3, about 500 kg were recovered during the first 2.5 days. This amount equaled 75% of the total mass recovery at E3.

Overall, well E3 responded quite as expected during the first 2.5 days of flushing. However, the absence of a secondary or even tertiary CD peak, which was expected as the result of a second and third breakthrough of the recycled CD solution, did not materialize. The reason for the absence of subsequent breakthrough peaks was dilution of the CD solution due to poor hydraulic control of the flushing system.

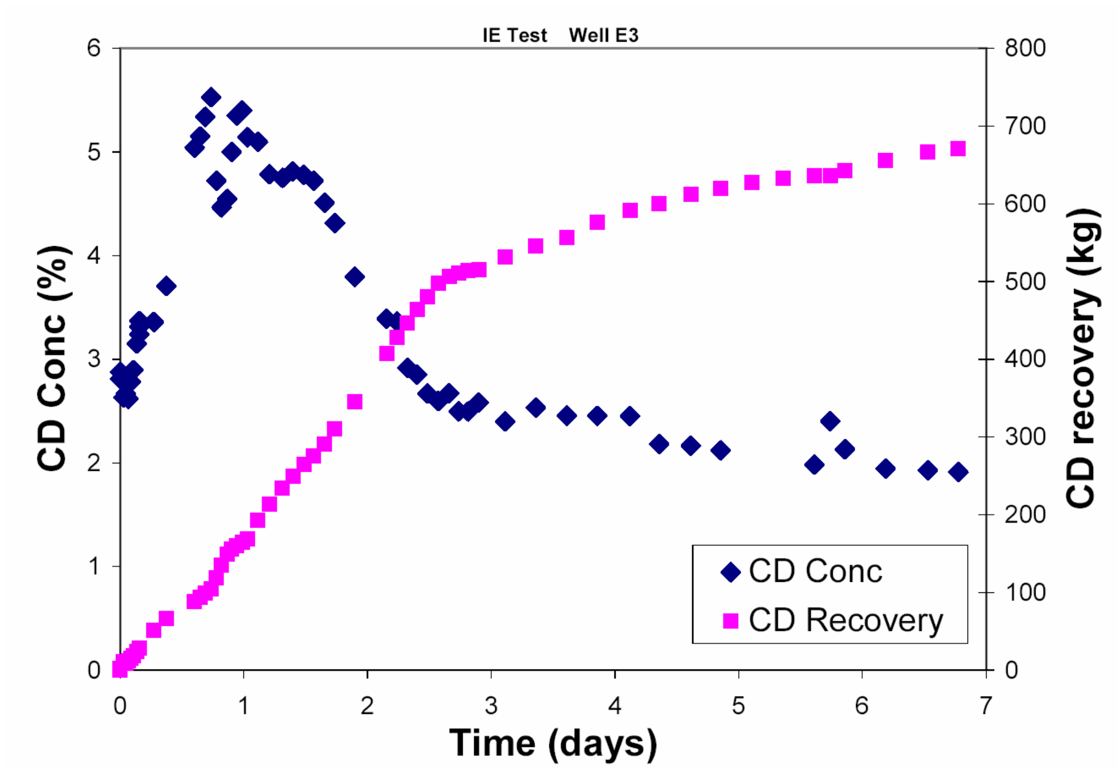



**Figure 5.12:** CD concentration and recovery data from extraction well E3 measured during injection/extraction test.

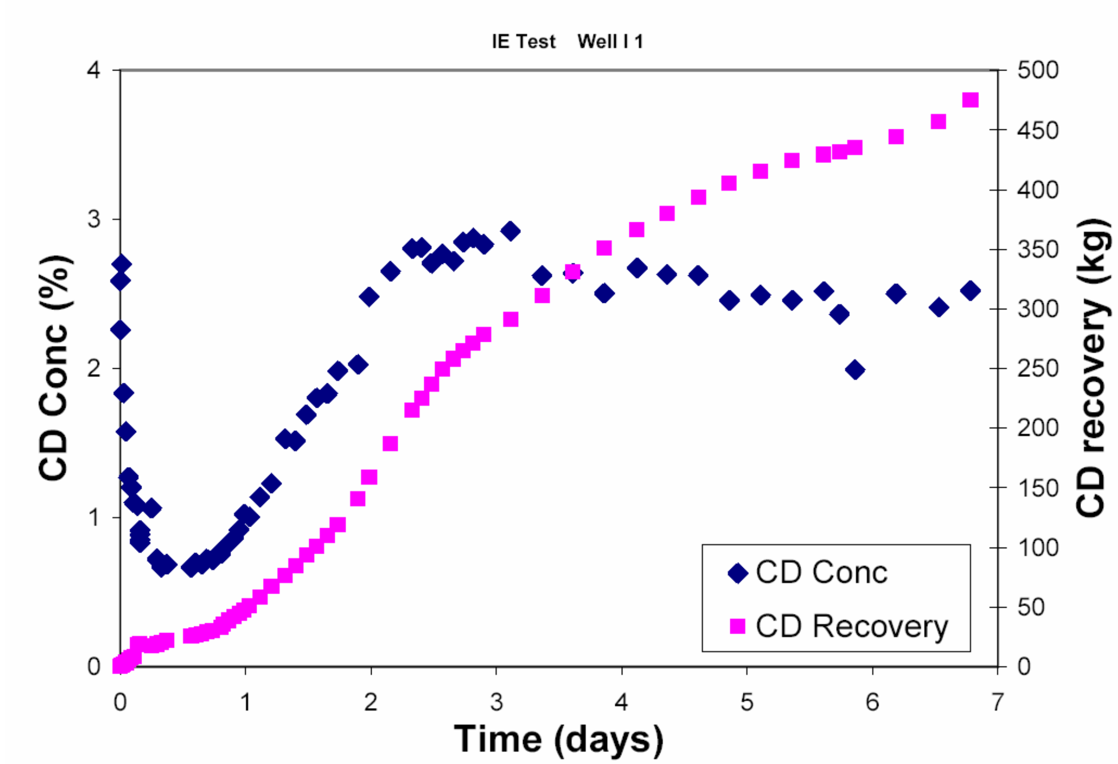



**Figure 5.13**: CD concentration and recovery data from extraction well I1 measured during injection/extraction test.

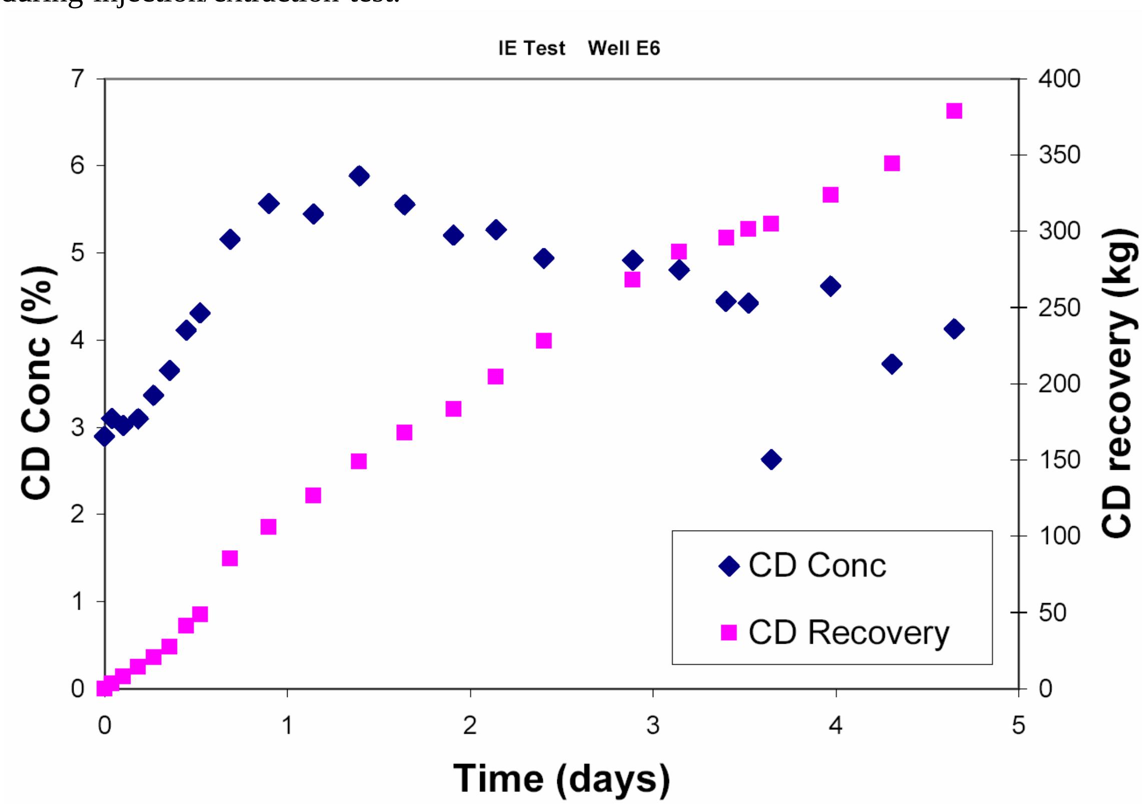



**Figure 5.14**: CD concentration and recovery data from extraction well E6 measured during injection/extraction test.

The second extraction well, I1 (see Figure 5.11 and 5.13), performed below expectation. Upon start of extraction at I1, CD concentration dropped from about 2.7% to less than 0.7% within 8 hours. The fact that there was any CD in the groundwater at the beginning of the extraction was related to remnants of CD solution from previous tests at well I1. During these equipment and hydraulic tests, about 600 gal of CD solution was injected into I1 and immediately retrieved to be processed in the air stripper, the PVP, and the UF. Although at the end of these prior tests the CD concentration was only 0.4%, it is likely that remnants from these tests were the cause for the elevated CD concentration at the beginning of the I/E test. Over the course of the first 48 hours, the CD concentration increased to 2.9% (or: 12.7% of the injected CD concentration) and remained essentially constant until the end of the test. The CD concentration was well below the performance criterion of 5% to 10%. Similar to well E3, there was no indication of any subsequent CD breakthrough. The observed CD concentration history indicates an even larger degree of dilution at well I1 than in well E3. Again, poor hydraulic control due to well clogging was the main cause for this performance. The amount of CD mass recovered from extraction well I1 was 475 kg (see Table 5.7).

The third extraction well, E6, cannot be compared directly with E3 and I1 because this well served first as an injection well and then as an extraction well. However, the CD concentration history of E6 further underlines the possible causes for the relative poor performance of the I/E test (Figure 5.14). When extraction began at E6, the CD concentration in the extract was near 3% (or: 13.1% of the injected CD concentration). It gradually increased to almost 6% (or: 26.3% of the injected CD concentration) over the following 36 hours. Afterwards, the CD concentration decreased continuously until the end of the test. The final CD concentration was 3.8%. As was the case for well I1 and E3, there was no indication of a secondary breakthrough peak. The total CD mass recovered from E6 was 379 kg (see Table 5.7).

The concentration history in well E6 indicates that a fraction of the initial CD slug was pushed upgradient (i.e., in southern direction) and away from the extraction wells. This portion of the initial 22.8% CD slug remained beyond the reach of the extraction wells while E6 was an injection well. Once E6 was converted into an extraction well, the slug was pulled back into E6 and was diluted to almost 6% in the process. The observations made on well E6 showed that even over a short distance (less than 4 meters) between the injection and extraction wells, hydraulic control of the flow field was hard to achieve. This finding was unexpected based on hydraulic simulations conducted prior to the injection/extraction test. These simulations indicated that the operation of the well field with two extraction wells and three injection wells should have resulted in a much lower degree of dilution and better hydraulic control. The principal reason for the discrepancy between observed and simulated flow was the continuous decrease of the injection rates in all injection wells as a consequence of iron precipitation (see Section 4). Because only as much water could be extracted as was possible to reinject, the loss of injection capacity resulted in a loss of extraction capacity. In consequence, the capture zone around each extraction well decreased and hydraulic control of the flow field was lost.

The injection/extraction test was terminated after (1) no secondary CD peaks appeared even after flushing several pore volumes, (2) the average CD concentration in the extracted water fell below the 5% performance criteria, and after (3) injection rates dropped from approximately 4.5 gpm to less than 1 gpm (see Figure 5.10).

| Extraction Well ID | Sum TCE | Theoret. P&T | Sum 1,1,1-TCA | Theoret. P&T | Sum 1,1-DCE | Sum Chloroform |
|---|---|---|---|---|---|---|
| | g | g | g | g | g | g |
| | | | | | | |
| I1 | 957 | 571 | 486 | 246 | 103 | BD |
| E 6 | 225 | 70 | 241 | 26 | 41 | BD |
| E 3 | 877 | 505 | 971 | 211 | 94 | BD |
| | | | | | | |
| **Total** | **2059** | **1146** | **1698** | **483** | **238** | **0** |
| | | | | | | |
| **SUM VOC** | **3995** | **g CDEF** | | | | |
| **SUM VOC** | **1867** | **g P&T** | | | | |

**Table 5.8:** Summary of the VOC mass recoveries achieved during the I/E test. Also included are the calculated mass recoveries for TCE and 1,1,1-TCA during (theoretical) P&T remediation (see text for details). The 1,1-DCE mass recoveries were estimated based on the average 1,1-DCE concentration measured during the pre-PTT (see Section 4 for details). Chloroform was below detection limit and therefore was not compared to P&T. The "Sum VOC" parameter was calculated by adding up the masses of all target compounds.

Figures 5.15 to 5.17 summarize the TCE concentrations measured in all three extraction wells during the injection/extraction test. These figures also include the TCE mass recovery analysis and a comparison with the (theoretical) performance of a conventional pump-and-treat system (P&T). Table 5.2 provides an overview of the contaminant masses recovered for every of the four target compounds. It also includes the expected mass recoveries for TCE and 1,1,1-TCA for a (theoretical) P&T system. The basis for calculating the (theoretical) performance of the P&T system were the average TCE (23.7 mg/L) and 1,1,1-TCA (10.2 mg/L) concentrations during the last stages of both PTTs. It was assumed that the contaminant concentrations measured during the last stages of the PTTs reflect the contaminant concentrations during a (theoretical) P&T remediation. This estimate is conservative because both PTTs lasted for only 10 days each. This period is short compared to the operation time of a typical P&T system. After a P&T begins to operate, contaminant concentration generally drop significantly and tend to approach an approximately steady level. This tailing is one of the main drawbacks of the P&T method. Thus, the performance of a conventional P&T system is almost certainly overestimated when the average contaminant concentrations obtained from the comparably short PTTs is applied as a performance measure for the P&T technology. Finally, the 1,1-DCE mass recoveries listed in Table 5.2 are estimates. For reasons outlined in Section 4 (i.e., uncertainty of 1,1-DCE analytical results), the 1,1-DCE masses were calculated based on an average concentration of 4.4 mg/L measured during the PTTs. This is also a conservative estimate, because the true, but uncertain 1,1-DCE concentrations were certainly higher during CDEF than during the PTTs.

Figure 5.15 shows that the TCE concentration in extraction well E3 increased to about 60 mg/L in response to CD flushing. The concentration remained at this level for about 2 days, then dropped to approximately 20 mg/L within a day, and continued to stay at that level until the end of the test. During the I/E test at well E3 a total of 877 g TCE was removed from the subsurface, which was 372 g (or 74%) more compared to the (theoretical) performance of a P&T system (see Table 5.2). The removal effectiveness of CDEF compared to P&T for 1,1,1-TCA was even greater (970 g to 211 g or 4.6 times enhancement, respectively; see Table 5.2). As was the case for the CD mass recovery, the TCE mass recovery rate decreased after about 3 days of CDEF. Figure 5.17 shows a correlation of the TCE concentration to the CD concentration. From this figure it is obvious that the TCE concentration is closely correlated to the CD concentration, i.e., it was high when the CD concentration was high and decreased together with the flushing agent's concentration. The data clearly underline that the CDEF technology was effectively increasing the contaminant removal.

The TCE concentrations and mass recoveries achieved in extraction well I1 are shown in Figure 5.16 (including comparison to a (theoretical) P&T). Over the course to the I/E test, the TCE concentration increase to almost 50 mg/L and a total of 957 g TCE were removed form the subsurface over a 7-day period. This was about 67.7 % more mass than what would have been removed during the same period of P&T (see Table 5.2). Overall, the TCE concentration did not fluctuate as sharply as in extraction well E3. Inspection of Figure 5.18 reveals that the TCE concentration began to gradually increase once the breakthrough of the CD occurred. Because the CD concentration did no change much after breakthrough, the TCE concentration also remained near constant. In case of 1,1,1-TCA, about 486 g were removed compared to 246 g during a (theoretical) P&T (97.9% increase; see Table 5.8).

During the I/E test, the TCE concentration in extraction well E6 increased rapidly to over 100 mg/L and then approached a fairly constant level of about 80 mg/L.. The TCE concentration remained at this level for the following 2.5 days. Afterwards, TCE concentrations decreased to about 40 mg/L at the end of the I/E test. Recall that well E6 was first used as an injection well and was converted into an extraction well two days into to test. Because of the shorter extraction time, the TCE mass recovered at E6 (225 g) is lower compared to wells E3 and I1. Relative to a (theoretical P&T remediation, 155.2 g more TCE were recovered (see Table 5.2). This is equivalent to a 3.2 fold solubility enhancement during CDEF. The enhancement was even higher in case of 1,1,1-TCA, where more than 9.1 times as much contaminant was recovered. Figure 5.19 shows again a close correlation between TCE and CD concentrations.

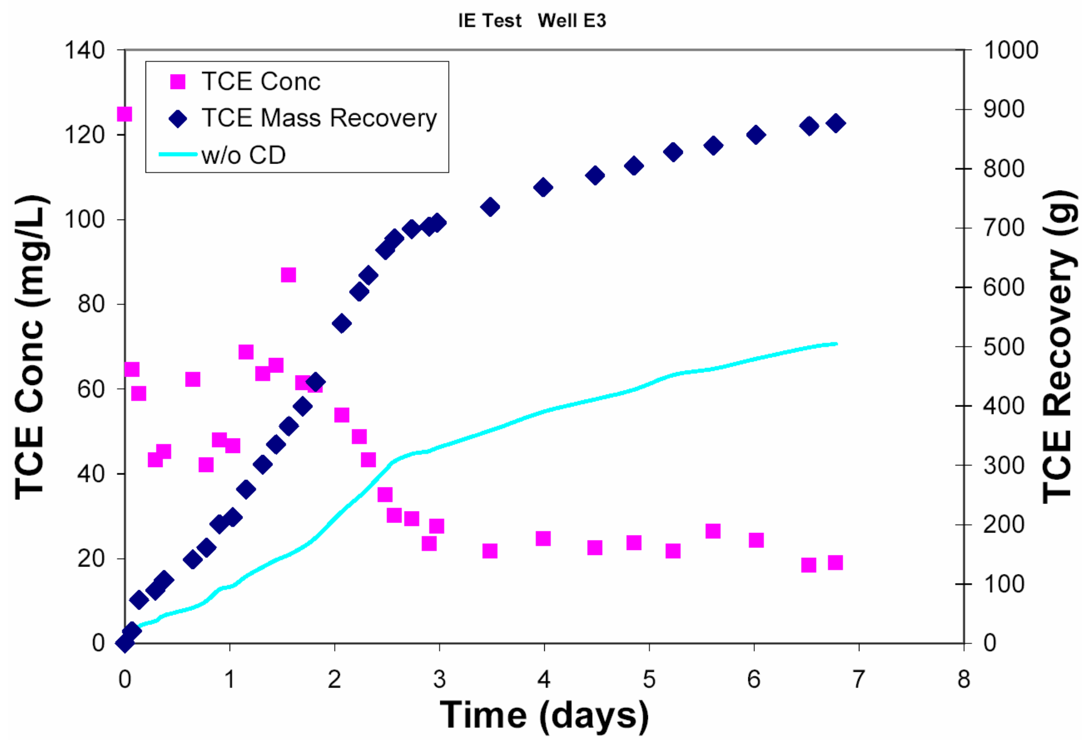



**Figure 5.15**: TCE concentration and recovery data from extraction well E3 measured during injection/extraction test. The solid light-blue line shows the (theoretical) performance of a conventional pump-and-treat system. Refer to text for details.

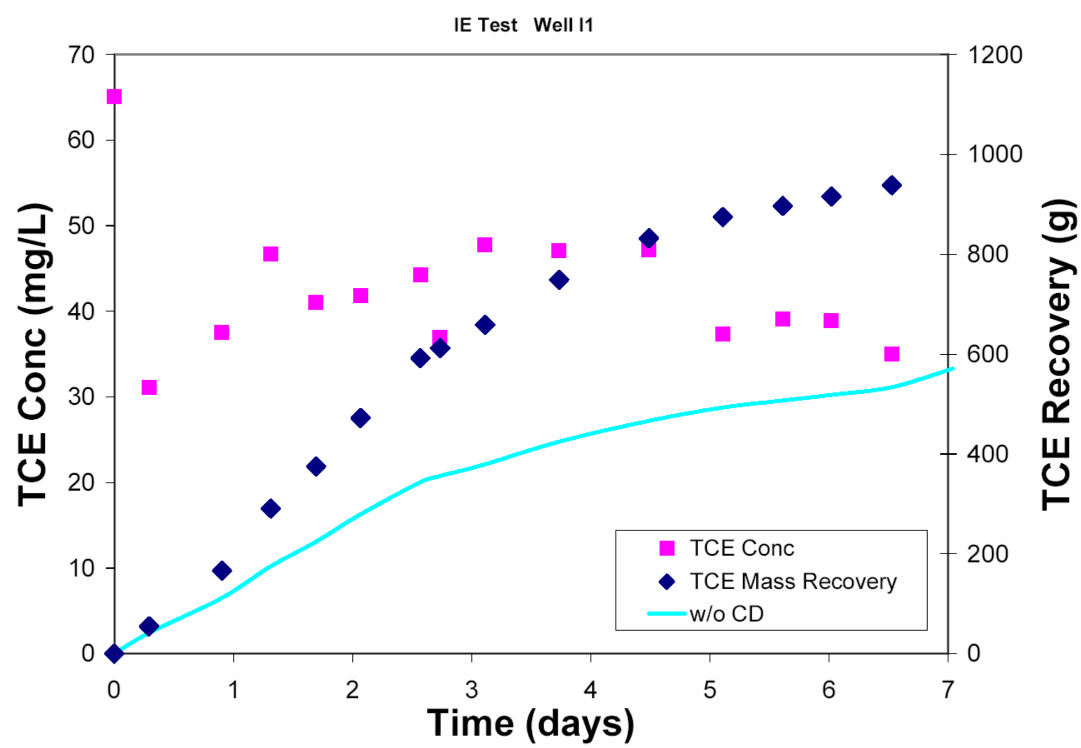



**Figure 5.16**: TCE concentration and recovery data from extraction well I1 measured during injection/extraction test. The solid light-blue line shows the (theoretical) performance of a conventional pump-and-treat system. Refer to text for details.

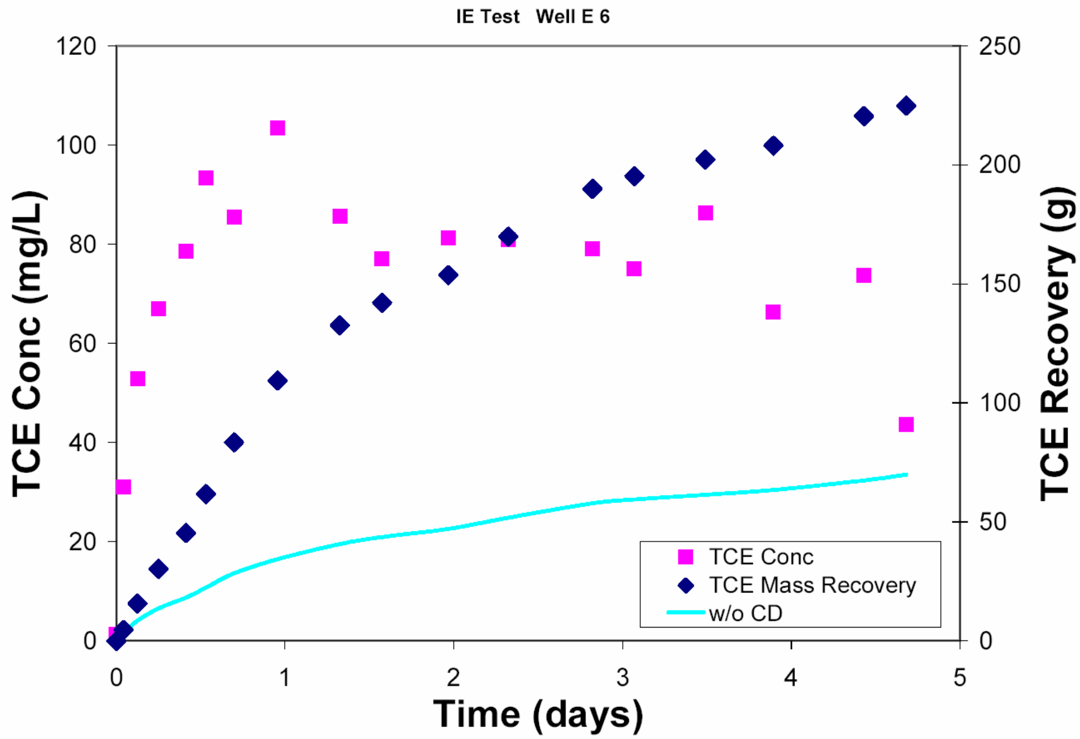



**Figure 5.17**: TCE concentration and recovery data from extraction well E6 measured during injection/extraction test. The solid light-blue line shows the (theoretical) performance of a conventional pump-and-treat system. Refer to text for details.

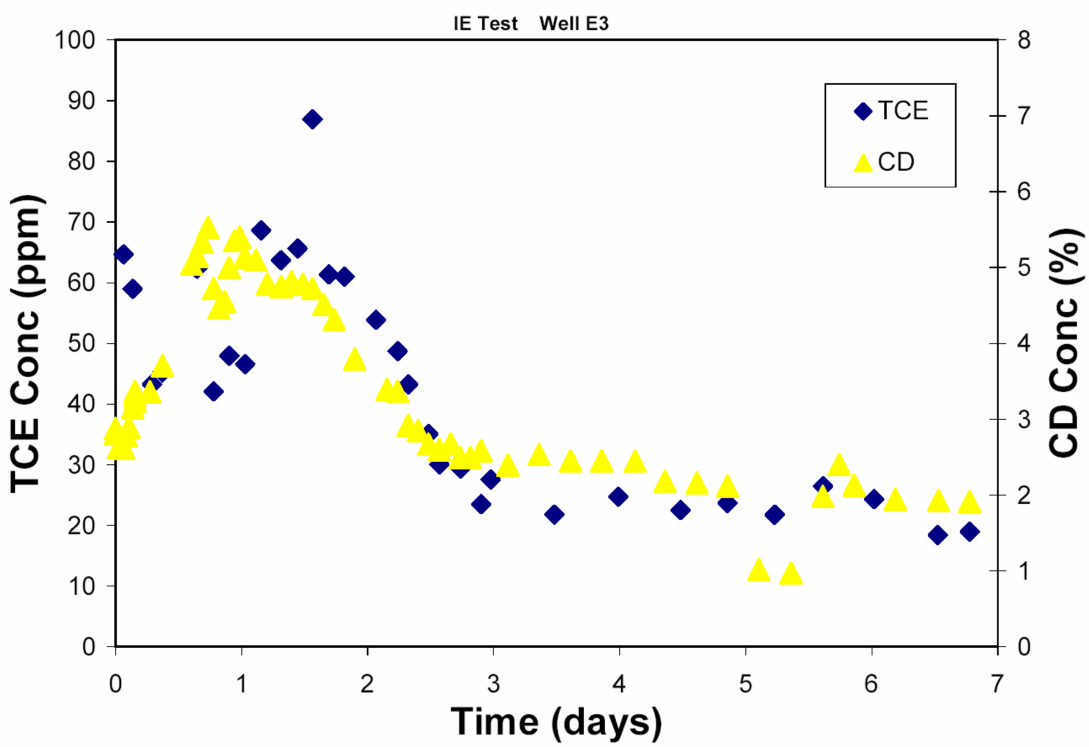



**Figure 5.18**: Correlation of TCE and CD concentration from extraction well E3 measured during injection/extraction test.

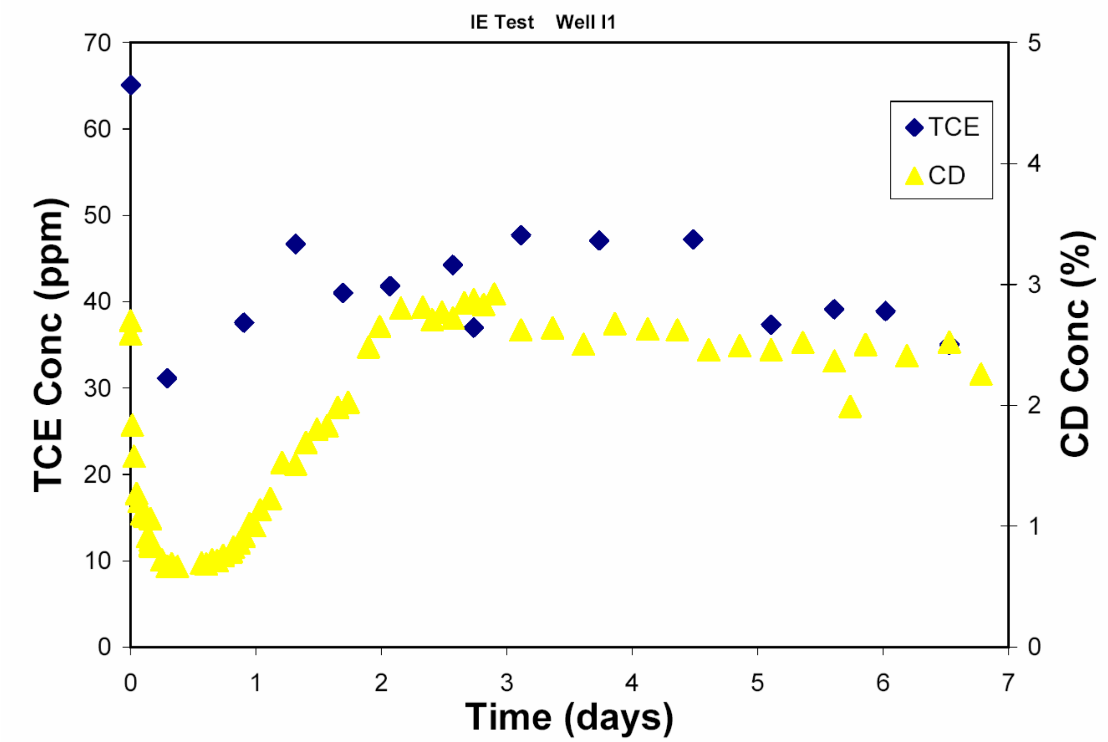



**Figure 5.19**: Correlation of TCE and CD concentration from extraction well I1 measured during injection/extraction test.

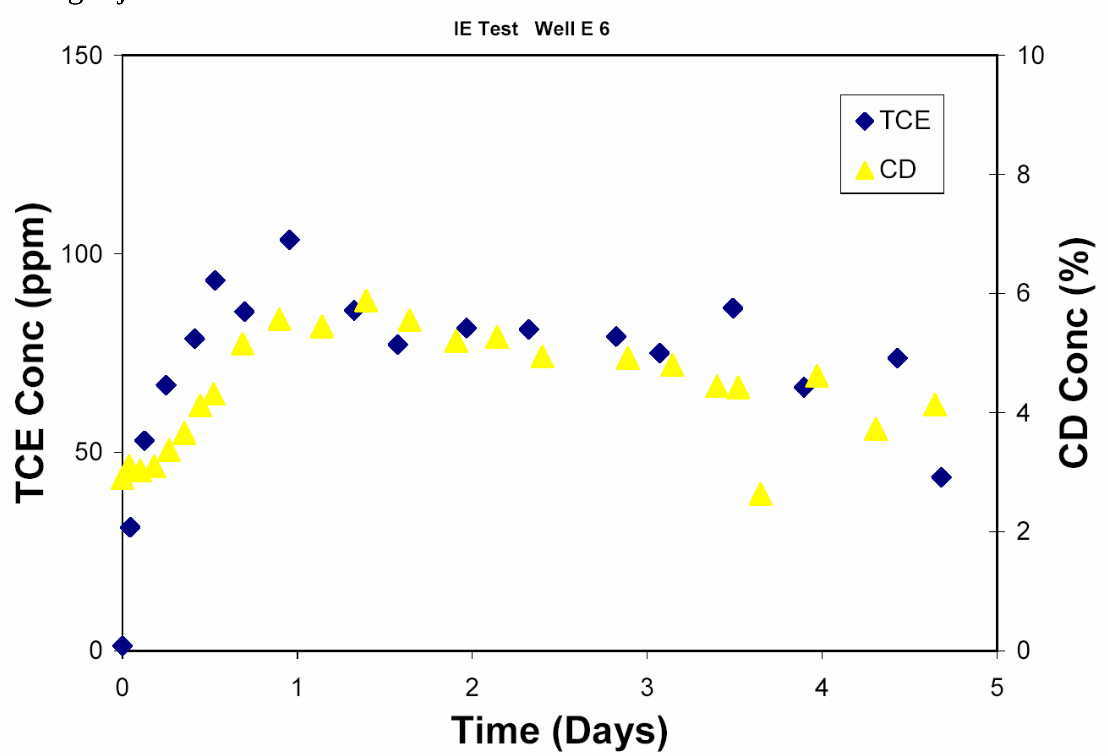



**Figure 5.20**: Correlation of TCE and CD concentration from extraction well E6 measured during injection/extraction test.

The following is a comparison of the expected to the actual quantitative and qualitative performance objectives applying to this part of the demonstration (see Table 4.1).

During the 7-day I/E test 3,995 g of VOC were removed (see Table 5.8). During the same period of time only 1,867 g of VOC (theoretically) would have been removed using a conventional P&T system. Compared to P&T, these numbers indicate an overall mass removal performance enhancement of 214% when using CDEF technology in an injection/extraction scheme. The increase in remediation performance translates directly into shorter remediation times, if P&T would be the remediation alternative to CDEF. Thus, the qualitative performance criteria "Faster Remediation" and "Reduction in Contaminant Source" (see Table 4.1) were satisfied. Also, because no CD reconcentration with the UF system was attempted during the I/E test, the demonstration setup was basically identical to a conventional P&T system. The only difference was that about one PV of CD flushing solution had to be injected at the beginning of the I/E test. The extra equipment requirement pertaining to the injection of CD were (1) providing a storage tank of sufficient size, an (2) set-up of a transfer line into the three injection wells. Because no specialized equipment or additional manpower is required, the qualitative performance objective "Ease of Use" (see Table 4.1) was also satisfied. The fourth qualitative performance criterion "Reduction in Contaminant Mobility: Smaller Plume" could not directly correlated to the I/E test performance since subsequent test also influenced the plume size.

With regard to the quantitative performance objectives (see Table 4.1), the I/E test had to be terminated prematurely to have a significant impact on the reduction of contaminant mass at Site 11. The recovered 3,995 g VOC equaled approximately 2.9 liter of DNAPL. Based on the PTT results, this volume resulted in a DNAPL mass reduction of about 7.8% over 7 days I/E operation. As discussed above, this is more than twice the mass reduction that would have been achieved using conventional remediation approaches. The amount of CD mass recovered during the I/E test was 79% of the injected mass, resulting in <1 flushes per CD molecule. This performance was below the expected >5 flushes per CD molecule. The main reason for the below expectation performance was that the capacity of the UF system was not large enough to operate in continuous mode (see discussion of UF performance in further below in this section). Operation in continuous mode was the prerequisite for effective CD recycling. Time constraints did not permit upgrading the UF system to the desired flow capacity.

The "maintenance" and "reliability" criteria defined for the I/E demonstration (see Table 4.1) were difficult to quantify since the test had to be terminated before any major equipment related problems appeared. The operation of the aboveground treatment system was simple and was confined to regular leak checks and flow rate readings. The sandfilter was still fully functioning when the test was terminated, which underlines that the iron precipitation was caused in the air stripper down the line from the sandfilter. The amount of iron precipitate that collected inside the air stripper did not influence the performance of the unit. With the exception of the clogged wells, the aboveground and below ground equipment proved to be robust, easy to operate, and required little maintenance or repair. At least during the short period of operation, the performance criteria defined for "maintenance" and "reliability" were satisfied.

The criteria list of "Factors affecting the technology performance" provided a daily flow rate of 68 $m^3$ per day (18,000 gpd) – equal to treating one PV per day. The realized flow rate was about 9 $m^3$ per day (2,500 gpd). The difference between the expected and actual flow rate was caused by focusing the treatment on a circa 7 times smaller treatment zone. The extent of the initial treatment volume was estimated based on a tentative well field constellation (see Appendix I: Demonstration Plan) that was revised based on numerical optimization of the flow field. The well field was further modified when during well installation it became evident that a trough at the base of the aquifer directed the DNAPL movement away from the center of the optimized well field. The original plan provided for a treatment capacity of one PV per day, the actual treatment capacity realized during the I/E test was 0.96 PV per day. Based on this measure, the performance criterion was met.

The maximum CD concentration in the extracted water during the I/E test was about 6% (see Figure 5.11), which was within the expected performance criterion of 5% to 10% CD concentration. However, the average CD concentration of all extraction wells combined ranged between 2% and 4%, which was below the expected performance. Again, poor hydraulic control of the flow field due to well clogging were the principal causes for the larger than anticipated dilution of the flushing solution. The total mass of CD recovered during the test was 1,525 kg, or 79% of the injected CD mass (1,936 kg). The average CD concentration of the recovered CD solution was about 4%. Had there been a second CD slug injected into the source zone, approximately 1,720 kg of CD mass would have been necessary to recondition the flushing solution to a 20 % CD content. This amount would have been necessary to make up for dilution and incomplete mass recovery. By using a UF unit, the amount of CD that had to be added would have been reduced 313% or about 550 kg (see Section 5.5.1 for discussion of the UF performance). Table 5.7 summarizes the test conditions during the injection/extraction test.

The DO content of the subsurface water decreased from near saturation prior to the I/E test to less than 5%. The DO decrease was greater than anticipated (50% DO during flushing) and may indicate that the (bio)degradation of the CD began soon after release to the subsurface. The relative fast onset of CD degradation in the field was not expected from prior lab studies. While there was no evidence that the degradation rate of the CD was fast enough to result in significant mass loss, the change from aerobic to anaerobic conditions contributed to the well clogging problems encountered during the I/E test. Conversely, the degradation of the CD may have the added benefit of facilitating the VOC (bio)remediation. However, without further study of biodegradation indicators, it is unreasonable to use the DO measurement to substantiate the potential bioenhancement properties of CD at this time. A long term CD fate study is currently in progress at Site 11 and will eventually provide evidence if cyclodextrin aided bioremediation is going on at the demonstration site.

The other factors listed in Table 4.1 were encountered as expected or did not influence the demonstration performance.

### 5.3.2 Cyclodextrin Push-Pull Tests (CPPT)

In response to the poor hydraulic control of the flow field during the I/E test, the CDEF treatment scheme was modified. Instead of continuously injecting and extracting the CD flushing solution from designated injection and extraction wells, selected wells served as both, injection (= push) and extraction (= pull) wells. The wells used during CPPT tests were identical to those wells used as extraction wells during the I/E test (i.e, wells E3, E6, and I1). Figure 5.21 shows the location of the CPPT test wells. The decision to use only these wells was made based on two main considerations: (1) sweep zone had to be within the treatment zone characterized by the two PTTs and (2) the CD injectate concentrations had to be similar compared to the I/E test (ca. 20%). In addition, the sweep PV during the CPPT had to be similar to I/E tests.

The CPPT tests discussed herein include single well CPPT tests that were conducted prior to the I/E test and multi-well CPPTs conducted afterwards. The principal purpose of the single well tests was to test the well field and the aboveground treatment system in preparation of the I/E test. They also served as test cases for the response of the well field to various CD injectate concentrations and feed/extraction rates. During the single well tests, CD solution was injected into one well at the time. During the later multi-well tests, CD solution was injected simultaneously into three wells. A total of eight CPPT tests were carried out, of which 5 were single well tests and 3 were multi-well tests. The multi-well tests were carried out immediately after the I/E tests. The CPPT test conditions, including the CD mass recovery percentages, are summarized in Table 5.9.

| Test ID | Well(s) | Average Injected CD Concentration % | Injected Volume liters | CD Mass Recovered (average) % | Injection Rate lpm (gpm) | Extraction Rate lpm (gpm) |
|---|---|---|---|---|---|---|
| **Single Well CPPT** | | | | | | |
| CPPT-1 | E 3 | 23.5 | 1188 | 77 | 4.5 (1.2) | 18.8 (5.0) |
| CPPT-2 | E 3 | 36.5 | 945 | 104.9 | 9.5 (2.5) | 15.2 (4.0) |
| CPPT-3 | I 1 | 30.1 | 2257 | 52.6 | 9.2 (2.4) | 12.2 (3.2) |
| CPPT-4 | E 6 | 30.9 | 1529 | 63.4 | 8.5 (2.3) | 8.1 (2.1) |
| CPPT-5 | E 6 | 5.3 | 7560 | 29.5 | 14.1 (3.7) | 5.6 (1.5) |
| **Multi-Well CPPT** | | | | | | |
| CPPT-6 | E3, E6, I1 | 20.7 | 7632 | 76.5 | 9.2 (2.4) | 12.1 (3.2) |
| CPPT-7 | E3, E6, I1 | 20.1 | 5783 | 114.6 | 8.8 (2.3) | 13.6 (3.6) |
| CPPT-8 | E3, E6, I1 | 22.3 | 3194 | 113.9 | 8.7 (2.3) | 12.8 (3.4) |

**Table 5.9:** Test conditions for single and multi-well CPPT tests. Injection and extraction rate averages are given in liters per minute (lpm) and gallons per minute (gpm; values in brackets). The reported CD mass recoveries for the multi-well CPPTs are the averages of all three extraction wells. Refer to Figures 5.22 to 5.26 for mass recoveries per well.

The injection and extraction rates during the single well CPPTs were varied systematically to study the response treatment zone to high and low feed rates and CD concentrations. The injection rates (= feed) ranged from 4.5 lpm to 14.1 lpm, while the extraction rates ranged from 5.6 lpm to 18.8 lpm. The CD concentration of the flushing solution injected into the subsurface ranged from 5.3% to 36.5%. The lowest injected volume was 945 liter (250 gal) during CPPT-2, while the highest volume was 7560 liter (2000 gal) during CPPT-5. The CD mass recoveries ranged from 29.5% to 104.5%. The CD solution recovered from the previous CPPT test was reused when possible. Figures 5.22 through 5.26 show the observed CD concentration in the extract and the cumulative CD mass recoveries during all single well CPPTs. Figures 5.27 through 5.29 show the results of the three multi-well CPPTs.

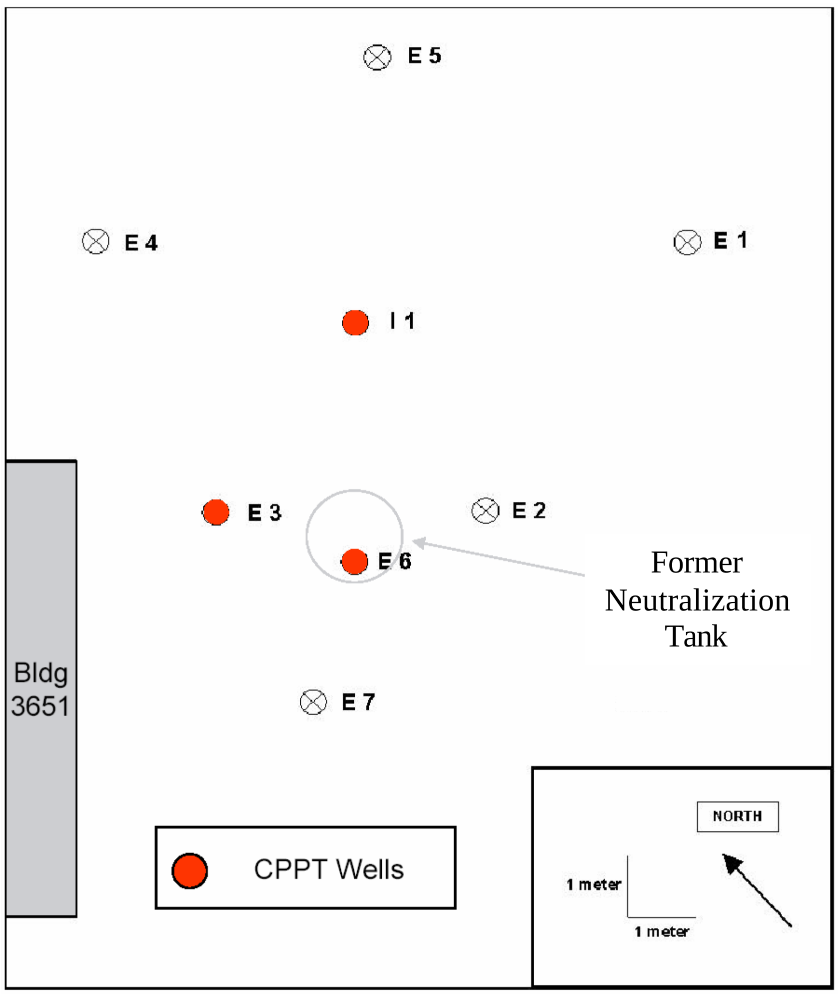



**Figure 5.21.:** Well field setup using during the single and multi-well CPPT tests. Note that the CPPT wells were identical to the extraction wells used during the I/E test (see Figure 5.9).

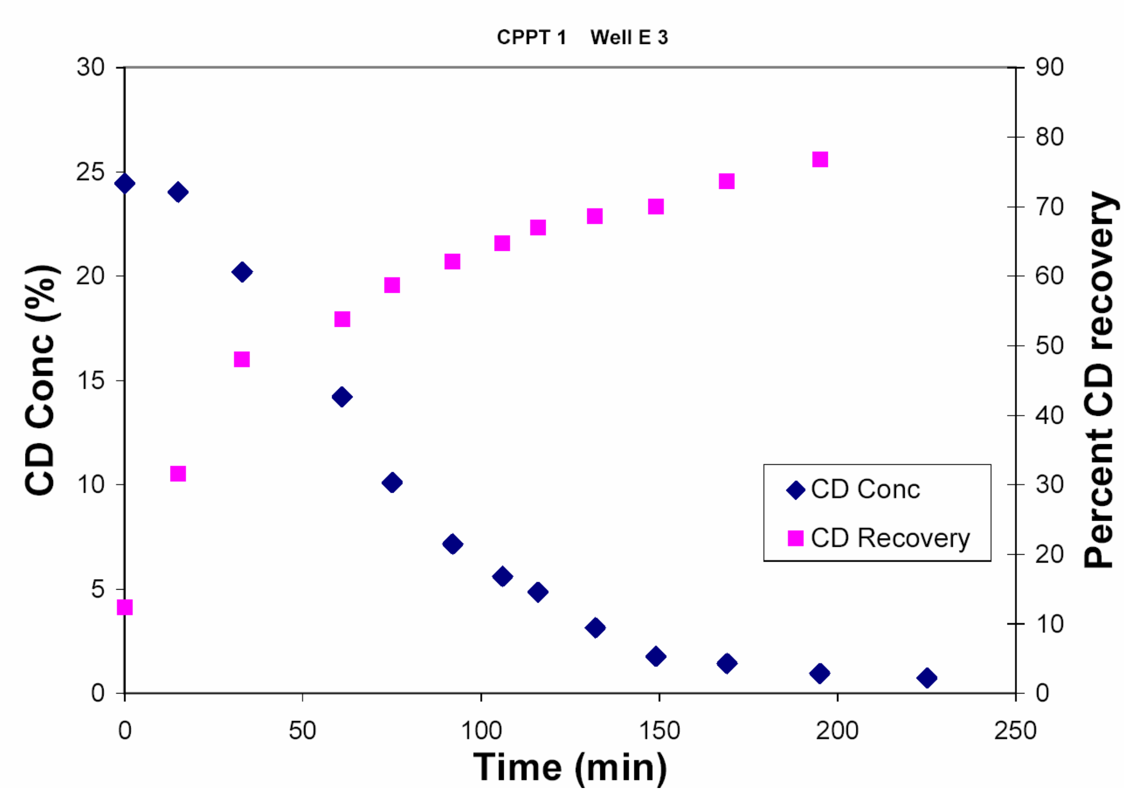



**Figure 5.22:** CD concentrations and recoveries determined during single-well CPPT-1.

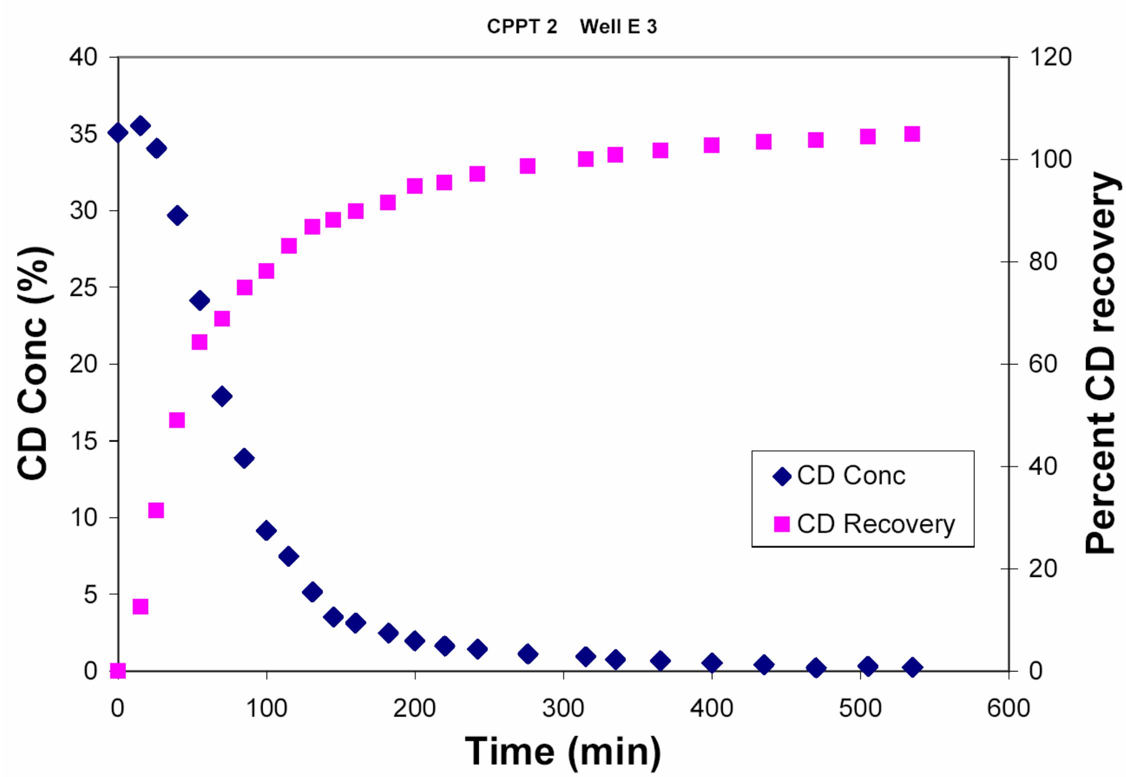



**Figure 5.23:** CD concentrations and recoveries determined during single-well CPPT-2.

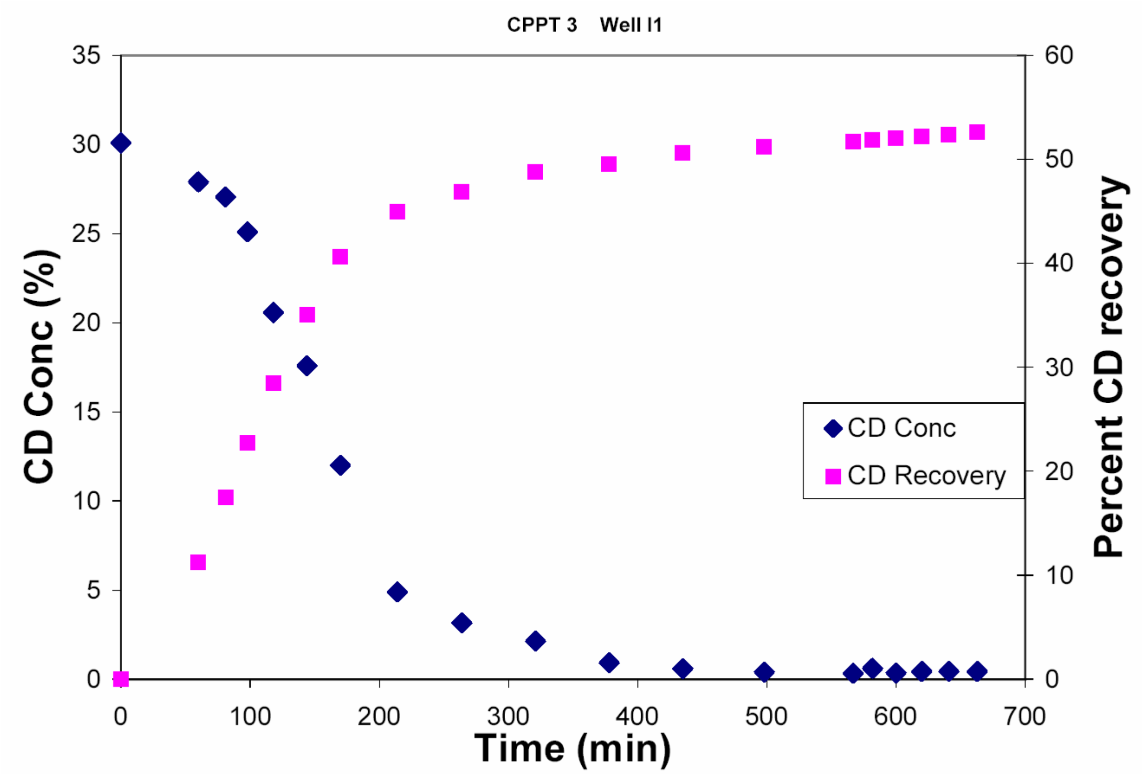



**Figure 5.24:** CD concentrations and recoveries determined during single-well CPPT-3.

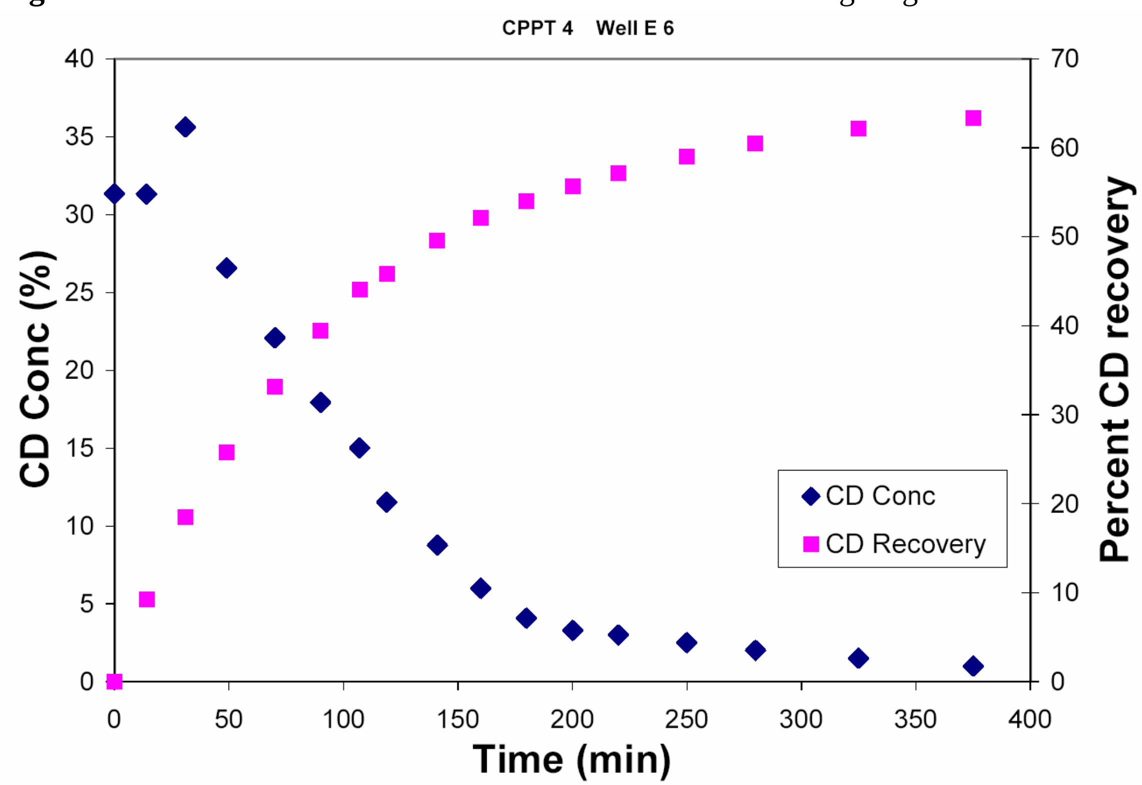



**Figure 5.25:** CD concentrations and recoveries determined during single-well CPPT-4.

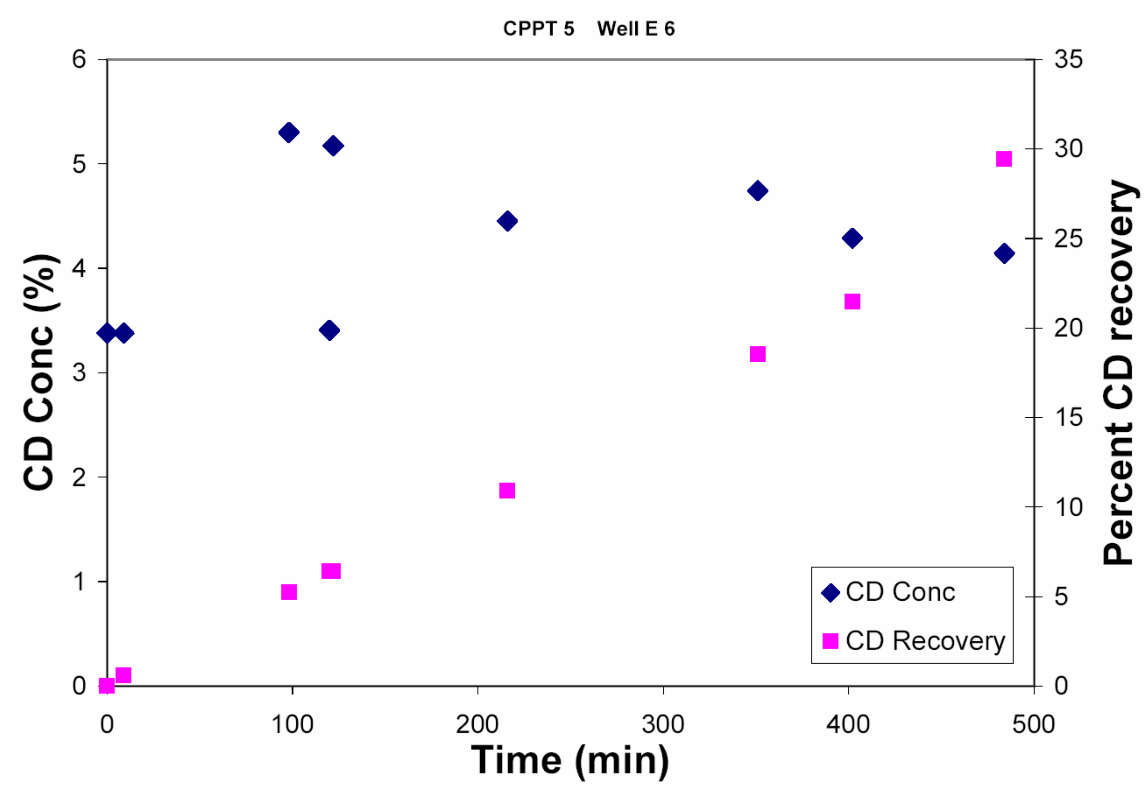



**Figure 5.26:** CD concentrations and recoveries determined during single-well CPPT-5.

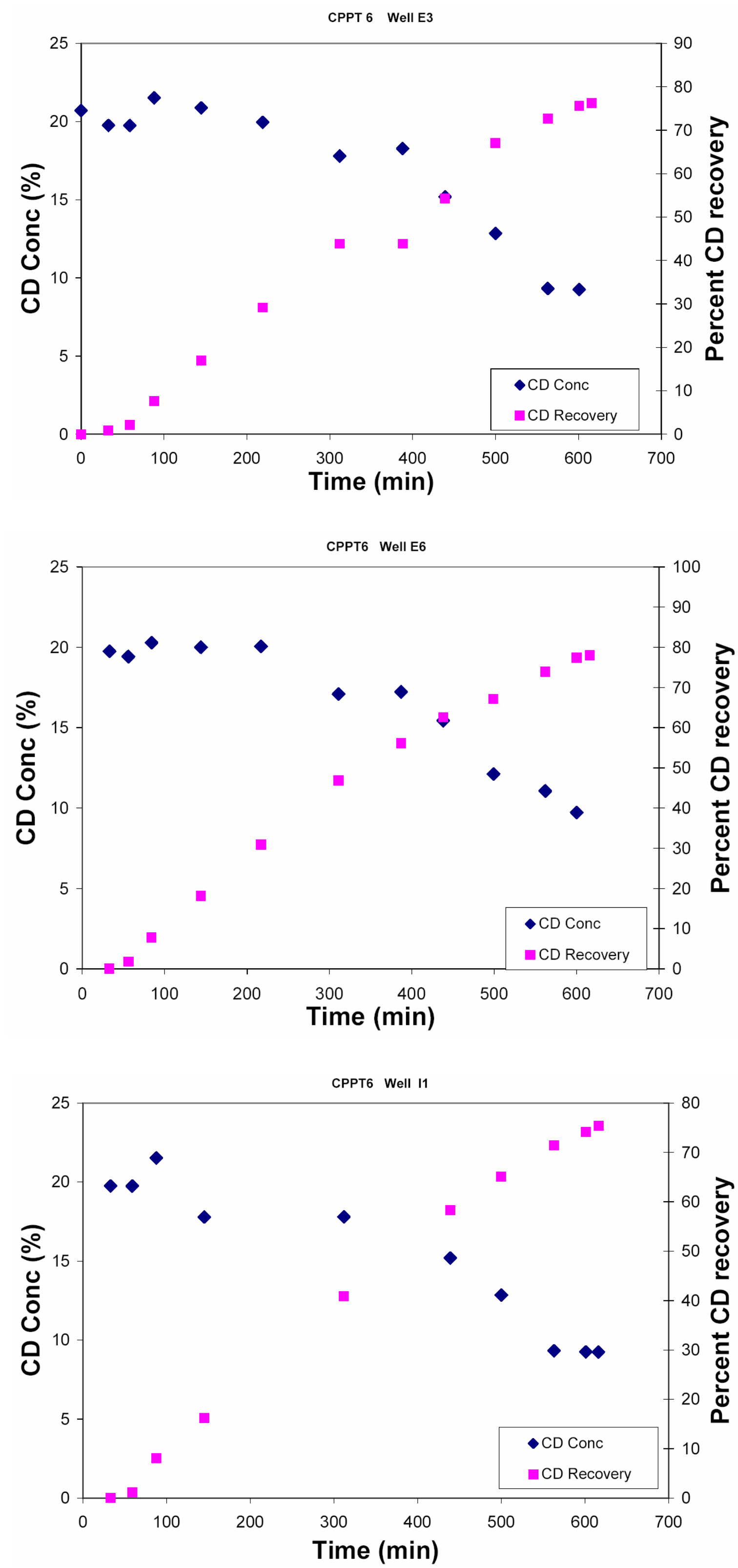



**Figure 5.27:** CD concentrations and recoveries determined during multi-well CPPT-6 at wells E3, E6, and I1 (from top to bottom).

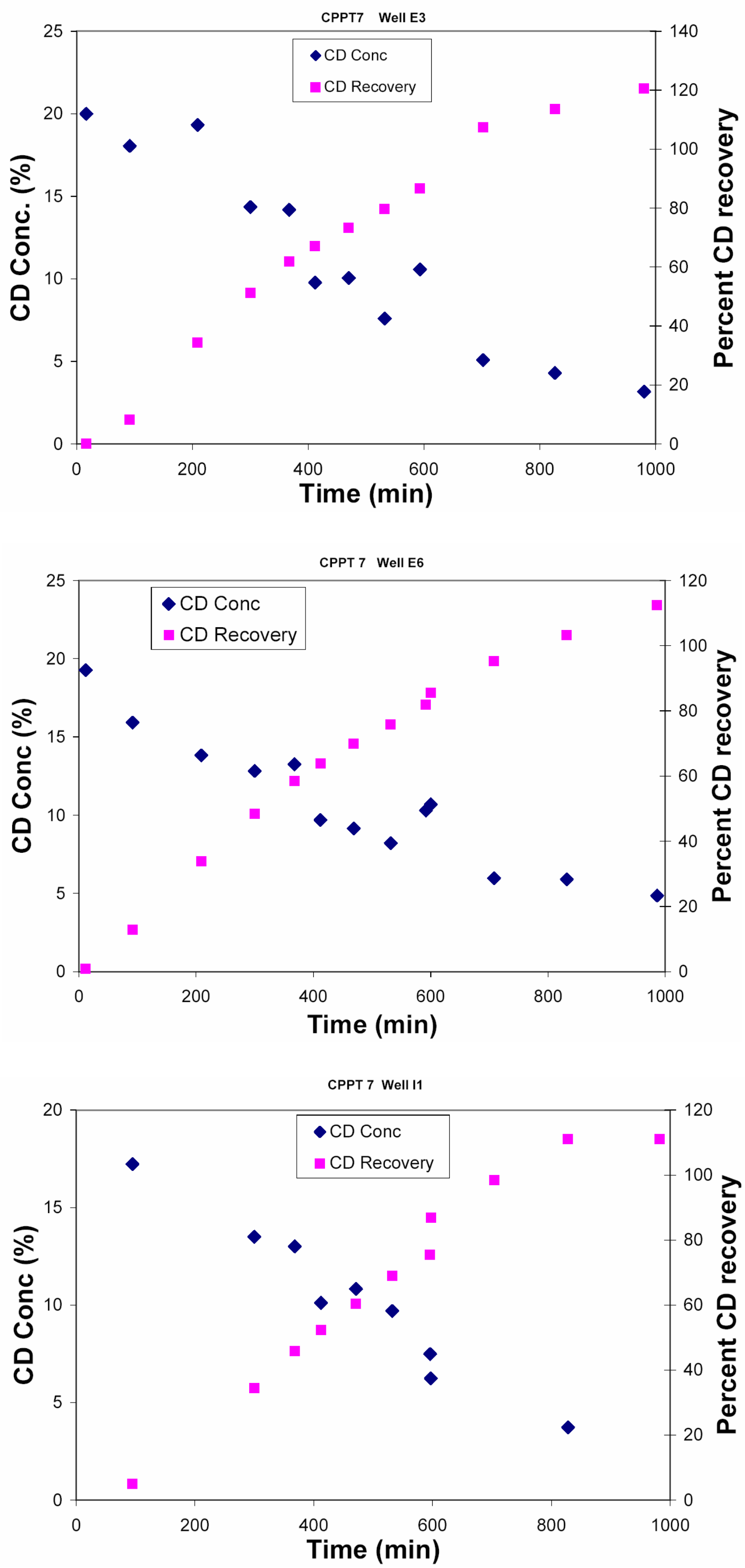



**Figure 5.28:** CD concentrations and recoveries determined during multi-well CPPT-7 at wells E3, E6, and I1 (from top to bottom).

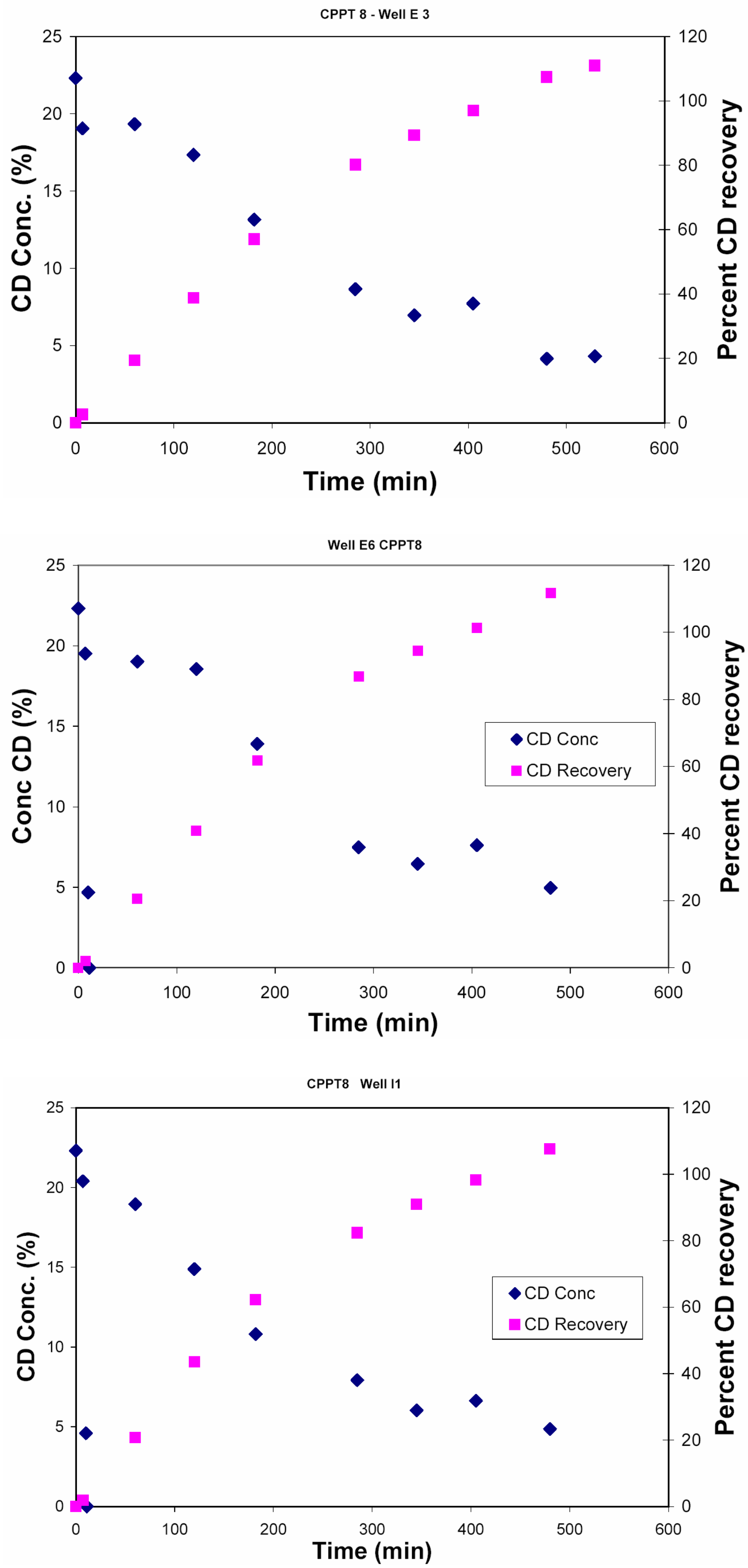


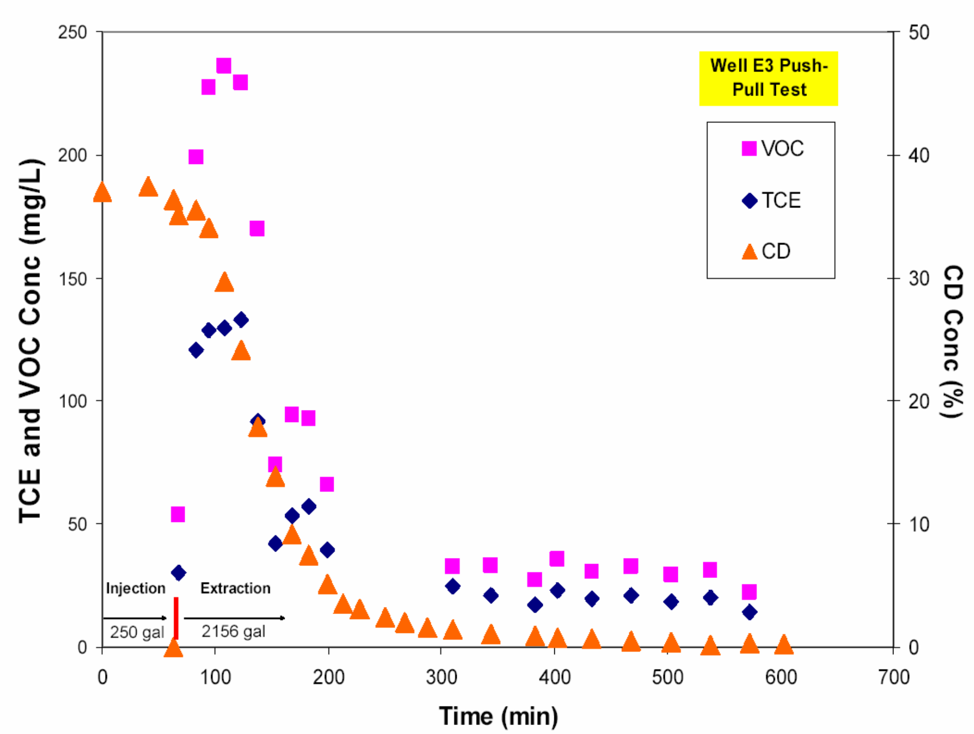

**Figure 5.29:** CD concentrations and recoveries determined during multi-well CPPT-8 at wells E3, E6, and I1 (from top to bottom).

All CD concentration graphs, except Figure 5.26 (CPPT-5), were very similar in shape. The CD concentrations of the first samples were in all cases almost identical to the injected CD solution. This indicates that the CD solution experienced little to no dilution at least in the immediate vicinity of the injection well. Later on, the CD concentrations dropped off more or less sharply. The volume of the injected CD slug together with the extraction rate determined how rapidly the CD concentration drop-off occurred. Typically, lower performance criterion for CD concentration (5%) was reached within the first 3 to 4 hours of extraction. During the single-well CPPTs, extraction was terminated when CD concentration in the extract was approximately 1% or lower. Only CPPT-5 was terminated when CD concentration were higher (ca. 4%, see Figure 5.26).

A distinct change in the removal effectiveness of the CD flushing solution was observed during the single-well CPPTs. For example, Figure 5.30 shows that during CPPT-2 about 76% of VOC were recovered when the CD concentration reached 10%. Once the CD concentration dropped below 5% to 10%, the contaminant removal efficiency of the flushing solution became not much different from that of a (theoretical) P&T system (as can be seen from the similar slopes of the P&T and CPPT mass recovery lines). Based on the lessons learned from the single-well CPPTs, the multi-well CPPTs were terminated before the CD concentration in the extract fell below 10%. The average CD concentration of the recovered multi-well CPPT flushing solution ranged from 10.0% to 16.3 %. The concentration of the recovered CD solution was readjusted to 20% using the 40% CD stock solution and then reinjected into the subsurface. The results shown in Figures 5.22 through 5.29 show that the recycled CD solution continued to enhance the TCE solubility.

During the three multi-well CPPT's, 3,459 kg CD were injected and 3356 kg were recovered. Of the recovered CD mass, 1,034 kg were reused. Without the UF system, 2,225 kg CD had to be added from the 40% CD stock solution to recondition the flushing solution to a 20% CD content. If the UF system had been used, this amount would have been reduced to 712 kg (see section 5.5.1 for details of UF performance). The fraction of reused CD mass during CPPT-7 was 69% and 0.33% during CPPT-8. The CD mass recoveries measured during the multi-well CPPTs (see Figures 5.27 through 5.29 and Table 5.9) ranged from 77% to over 114%. The overall CD reuse factor, defined here as the ratio of the total CD mass injected divided by the recycled CD mass, was 3.4. The planned reuse factor was 5 or higher (see Table 4.1). Compared to the I/E test, the reuse factor for the multi-well CPPT test was significantly higher (0.79 compared to 3.4). This difference demonstrated that the CD flushing solution can be more effectively reused in a push-pull application scheme.

Figures 5.31 through 5.38 show TCE concentration and cumulative TCE mass recoveries observed during all CPPT tests. The TCE mass recovery results achieved by applying CDEF technology were compared to those of a (theoretical) pump-and-treat system without CD present. During the CPPT tests, the TCE concentration increased to more than 270 mg/L (CPPT 4, Well E6), which was an solubility enhancement 11.4 times over the TCE background concentration. The TCE mass recovered during the CPPT tests ranged from about 90 g to 470 g.



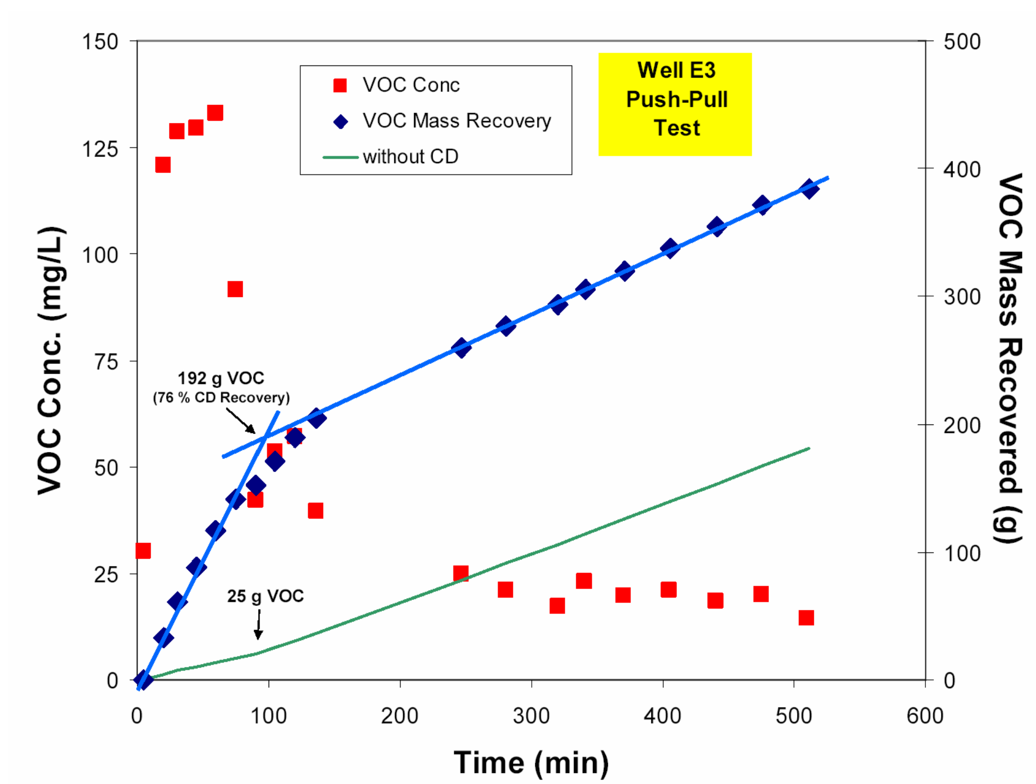




**Figure 5.30:** Results of CPPT-2 on well E3. Shown on top are the measured CD, TCE, and VOC concentration. The graph below demonstrates that there was a distinct change in slope during the extraction of the flushing solution. Up to the point, 76% of the VOC mass was recovered. Extraction beyond this point was about as effective as P&T.

| Test/Well ID | Sum TCE g | Theoret. P&T g | Sum 1,1,1-TCA g | Theoret. P&T g | Sum 1,1-DCE g | Sum Chloroform g |
|---|---|---|---|---|---|---|
| Single-Well CPPT | | | | | | |
| CPPT-1 E 3 | 189 | 100 | 137 | 43 | 19 | BD |
| CPPT-2 E3 | 243 | 186 | 222 | 64 | 36 | BD |
| CPPT-3 I1 | 470 | 202 | 175 | 80 | 36 | BD |
| CPPT-4 E6 | 449 | 103 | 850 | 45 | 17 | BD |
| CPPT-5 E6 | 260 | 61 | 240 | 26 | 12 | BD |
| ***Sum single-well*** | ***1610*** | ***651*** | ***1625*** | ***259*** | ***120*** | |
| Multi-Well CPPT | | | | | | |
| CPPT-6 E3 | 166 | 59 | 75 | 25 | 11 | BD |
| CPPT-6 E6 | 399 | 61 | 348 | 26 | 11 | BD |
| CPPT-6 I1 | 219 | 62 | 107 | 27 | 11 | BD |
| CPPT-7 E3 | 221 | 103 | 139 | 45 | 20 | BD |
| CPPT-7 E6 | 455 | 97 | 472 | 42 | 19 | BD |
| CPPT-7 I1 | 343 | 97 | 231 | 48 | 20 | BD |
| CPPT-8 E3 | 89 | 53 | 42 | 23 | 10 | BD |
| CPPT-8 E6 | 214 | 53 | 225 | 23 | 10 | BD |
| CPPT-8 I1 | 115 | 53 | 96 | 23 | 11 | BD |
| ***Sum multi-well*** | ***2219*** | ***640*** | ***1735*** | ***281*** | ***122*** | |
| | | | | | | |
| **Total, all CPPT** | **3828** | **1291** | **3360** | **539** | **241** | |
| | | | | | | |
| **Sum VOC** | **7430** | **g CDEF** | | | | |
| **Sum VOC** | **2072** | **g P&T** | | | | |

**Table 5.10:** Summary of the VOC mass recoveries achieved during CPPT tests. Also included are the calculated mass recoveries for TCE and 1,1,1-TCA during (theoretical) P&T remediation (see text for details). The 1,1-DCE mass recoveries were estimated based on the average 1,1-DCE concentration measured during the pre-PTT (see Section 4 for details). Chloroform was below detection limit and therefore was not compared to P&T. The "Sum VOC" parameter was calculated by adding up the masses of all target compounds.

Table 5.10 summarizes the overall TCE mass recoveries and provides mass recoveries for other VOCs not shown in Figures 5.31 through 5.38. Table 5.1 also provides a comparison of CPPT mass removal efficiency to that of a (theoretical) P&T remediation. As for the I/E test, the basis for calculating the (theoretical) performance of the P&T system was the average TCE (23.7 mg/L) and 1,1,1-TCA (10.2 mg/L) concentration measured during the last stages of both PTTs. Again, this is a conservative estimate and the performance of a conventional P&T system is almost certainly overestimated using these values. For reasons outlined in Section 4 (i.e., uncertainty of 1,1-DCE analytical results), the 1,1-DCE masses were calculated based on an average concentration of 4.4 mg/L measured during the PTTs. This is also considered a conservative approach, because the true, but uncertain 1,1-DCE concentrations during CDEF were certainly higher than during the PTTs.

Similar to the I/E test, the TCE concentration closely followed the CD concentration measured during the CPPT test, i.e., high CD concentrations coincided with high TCE concentrations (see Figures 5.39 through 5.46).

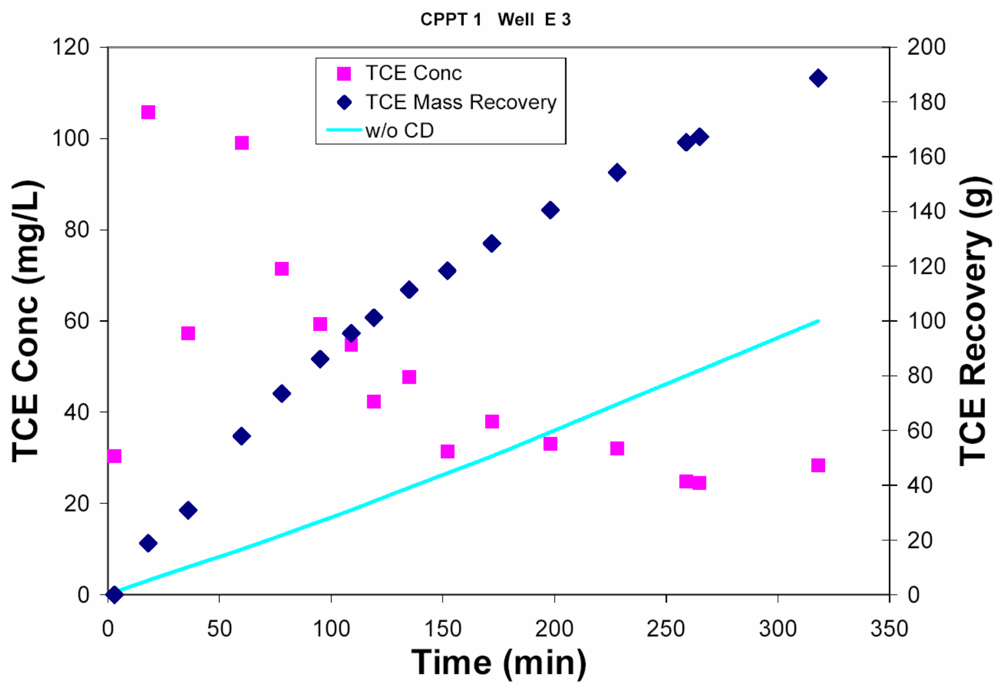



**Figure 5.31:** TCE concentration and cumulative TCE mass recoveries observed during single well CPPT 1 on well E3. The TCE mass recovery results achieved by applying CDEF technology are shown in comparison with those of a (theoretical) pump-and-treat system without CD present.

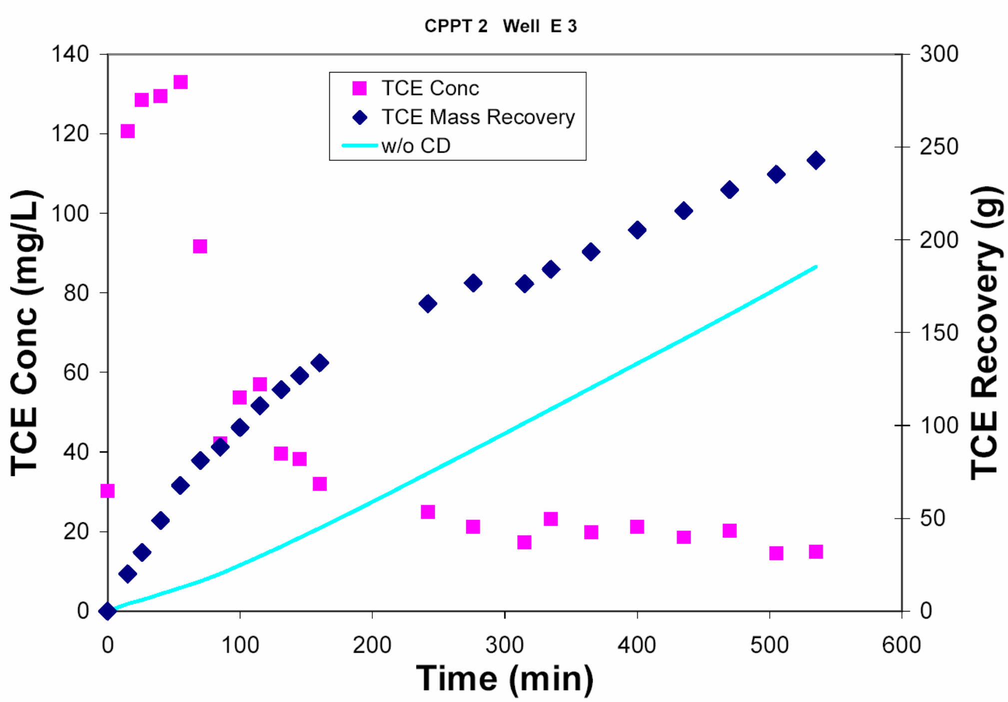



**Figure 5.32:** TCE concentration and cumulative TCE mass recoveries observed during single well CPPT 2 on well E3. The TCE mass recovery results achieved by applying CDEF technology are shown in comparison with those of a (theoretical) pump-and-treat system without CD present.

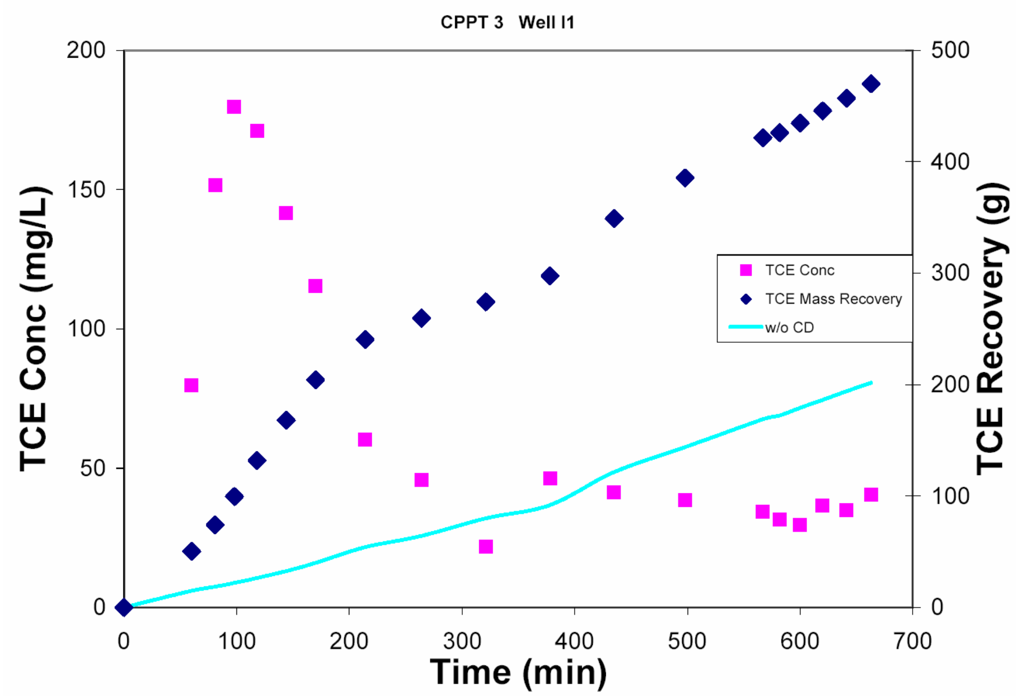



**Figure 5.33:** TCE concentration and cumulative TCE mass recoveries observed during single well CPPT 3 on well I1. The TCE mass recovery results achieved by applying CDEF technology are shown in comparison with those of a (theoretical) pump-and-treat system without CD present.

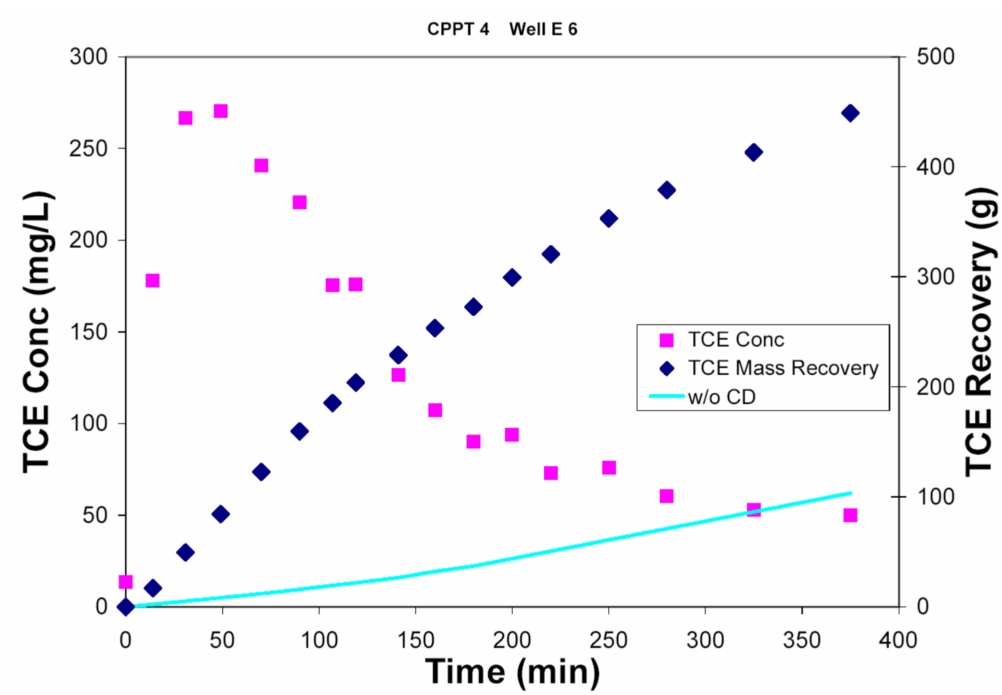



**Figure 5.34:** TCE concentration and cumulative TCE mass recoveries observed during single well CPPT 4 on well E6. The TCE mass recovery results achieved by applying CDEF technology are shown in comparison with those of a (theoretical) pump-and-treat system without CD present.

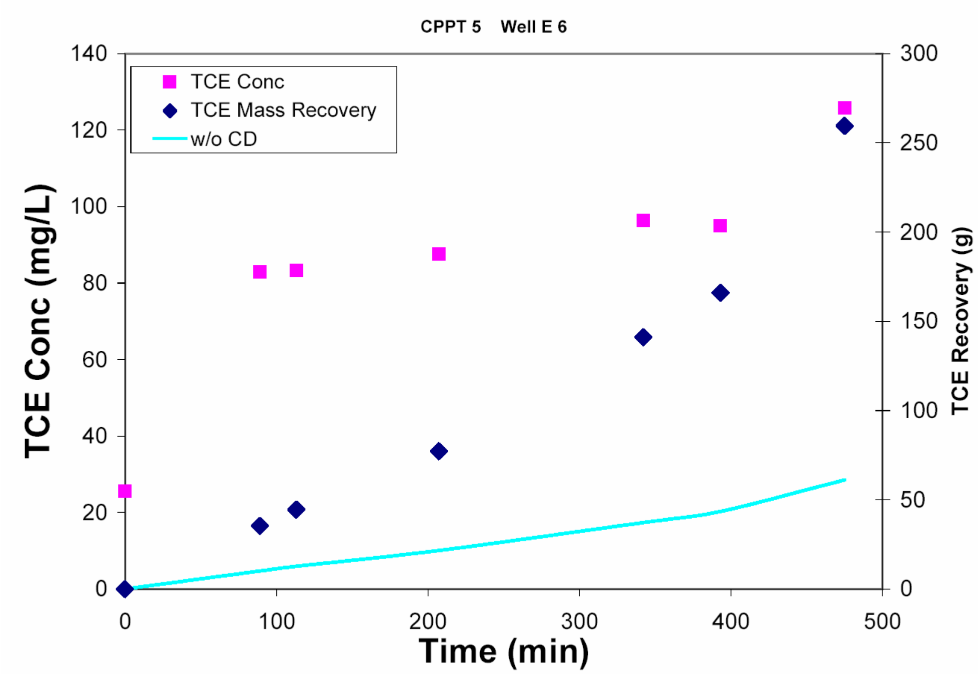



**Figure 5.35:** TCE concentration and cumulative TCE mass recoveries observed during single well CPPT 5 on well E6. The TCE mass recovery results achieved by applying CDEF technolo gy are shown in comparison with those of a (theoretical) pump-and-treat system without CD present.

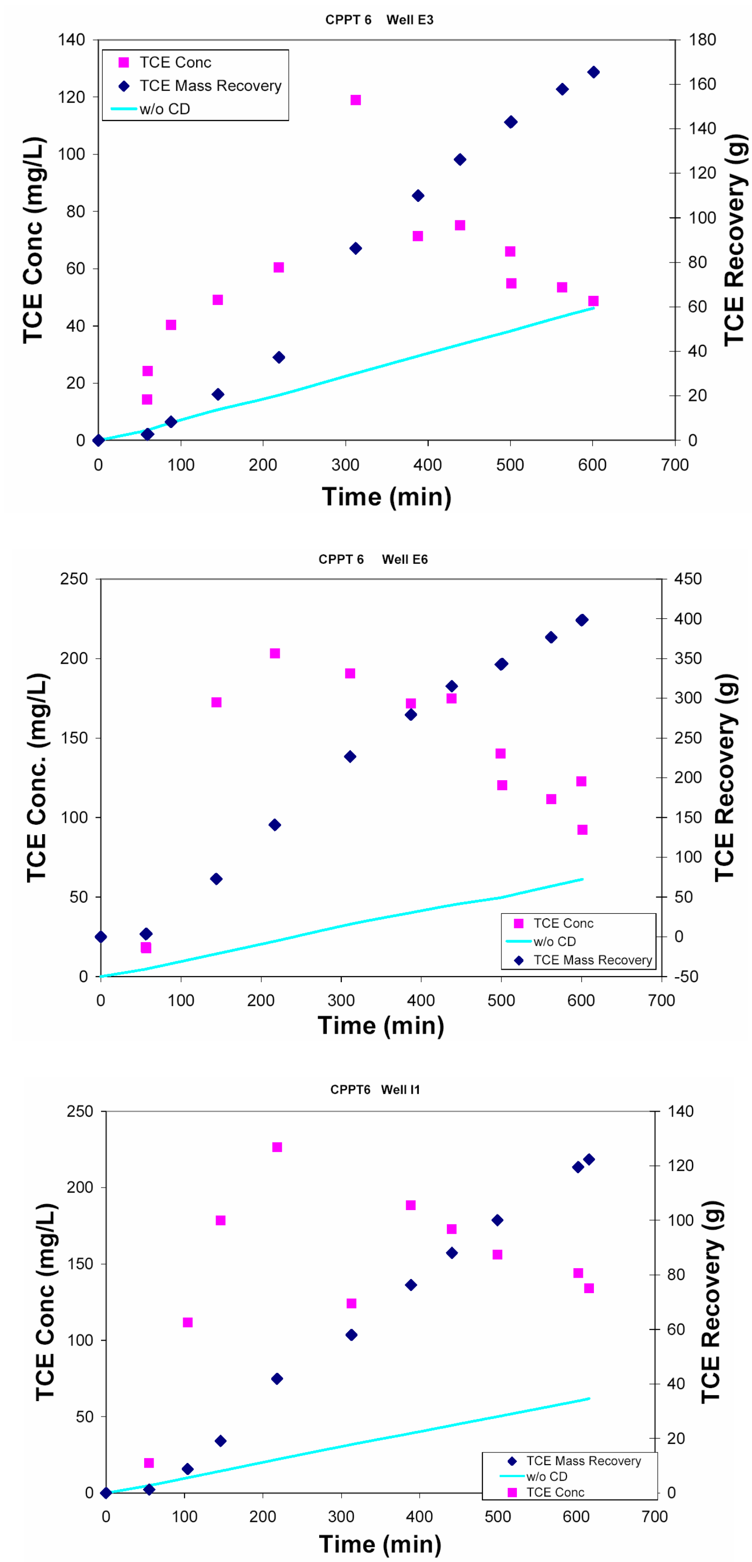



**Figure 5.36:** TCE concentration and cumulative TCE mass recoveries observed during multi-well CPPT 6 on well E3, E6, and I1 (from top to bottom). The TCE mass recovery results achieved by applying CDEF technology are shown in comparison with those of a (theoretical) pump-and-treat system without CD present.

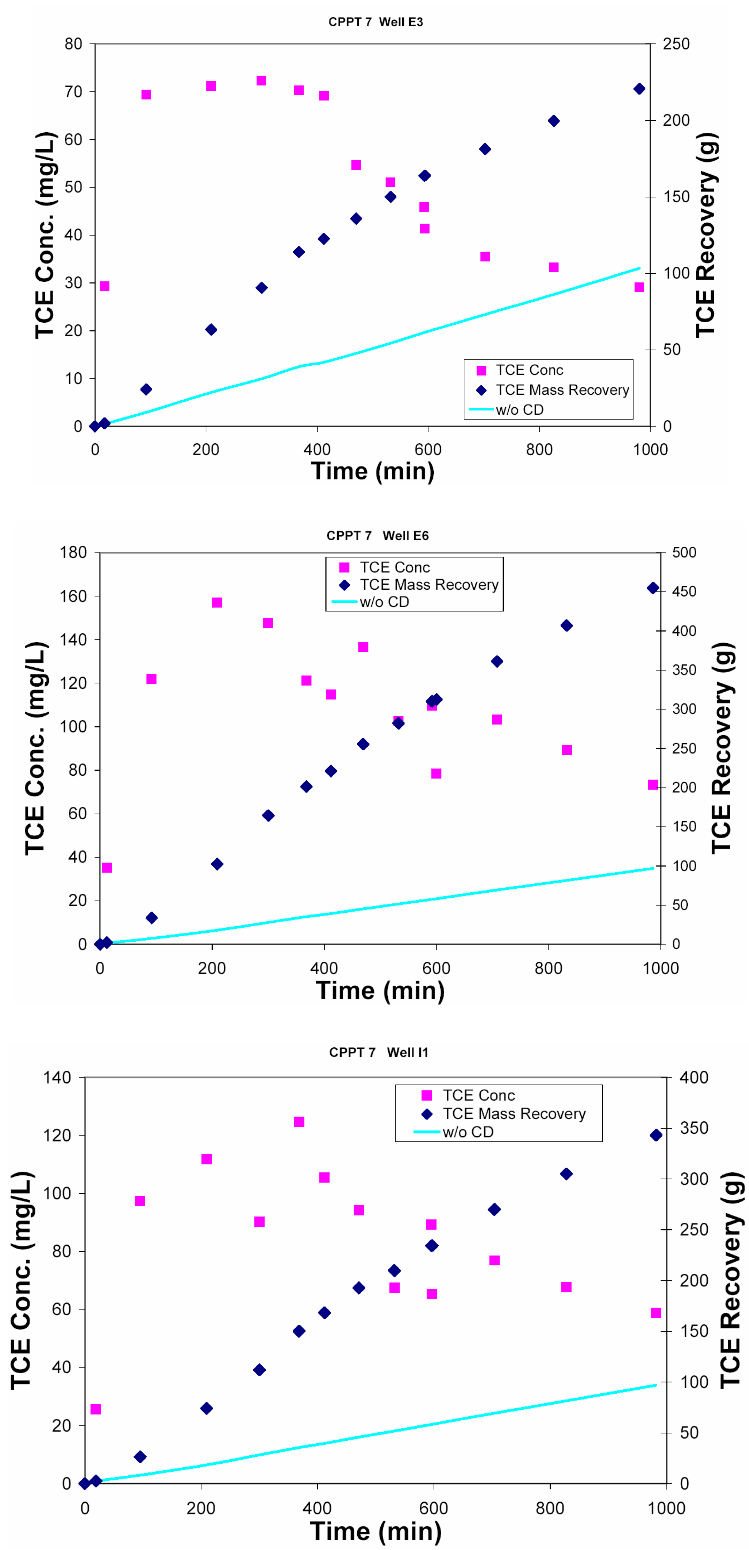



**Figure 5.37:** TCE concentration and cumulative TCE mass recoveries observed during multi-well CPPT 7 on well E3, E6, and I1 (from top to bottom). The TCE mass recovery results achieved by applying CDEF technology are shown in comparison with those of a (theoretical) pump-and-treat system without CD present.

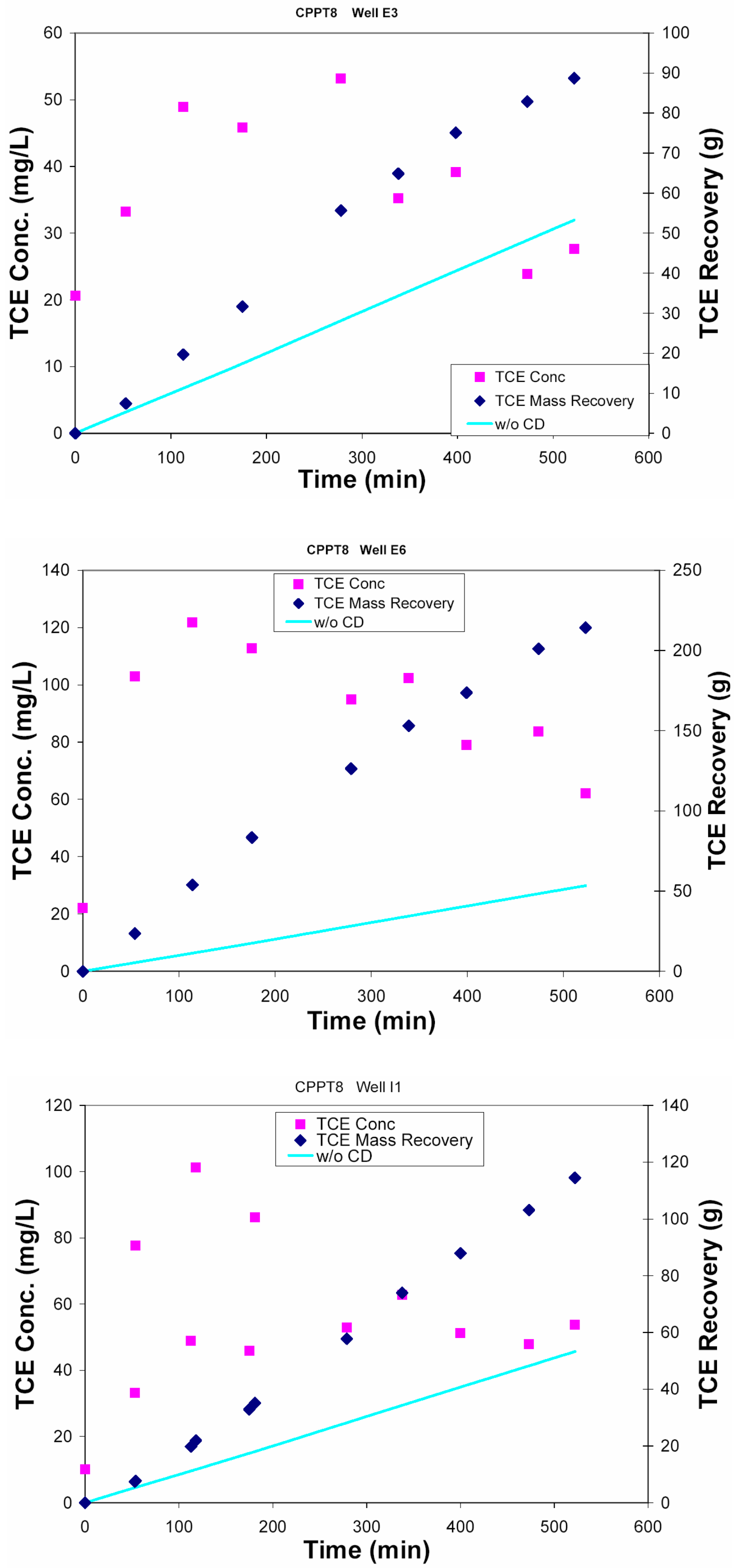



**Figure 5.38:** TCE concentration and cumulative TCE mass recoveries observed during multi-well CPPT 8 on well E3, E6, and I1 (from top to bottom). The TCE mass recovery results achieved by applying CDEF technology are shown in comparison with those of a (theoretical) pump-and-treat system without CD present.

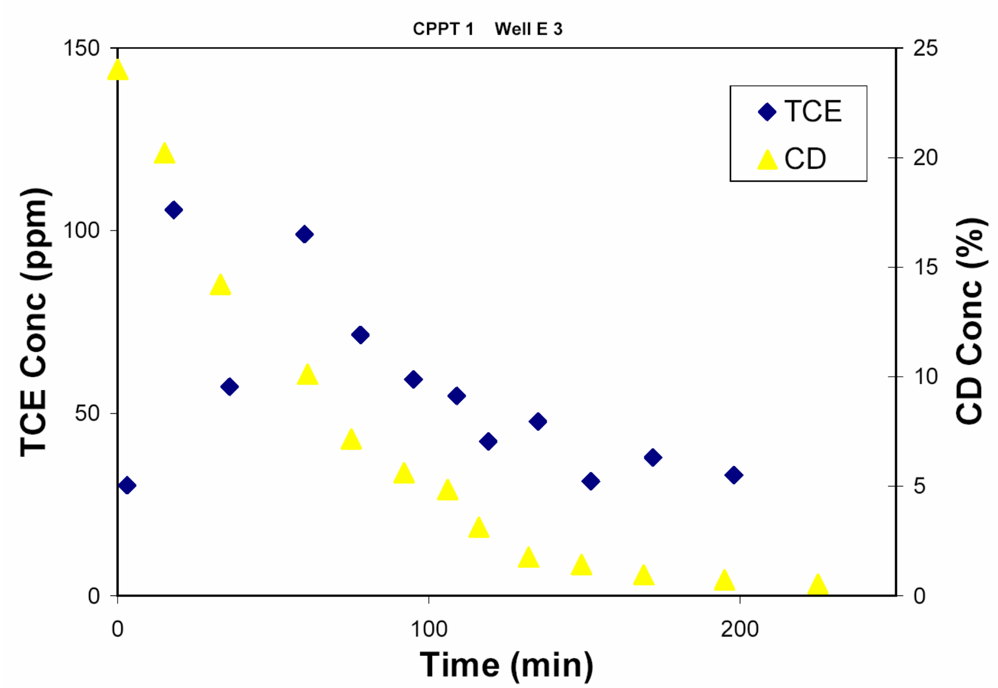



**Figure 5.39:** Comparison of measured TCE and CD concentration during single well CPPT-1 tests on well E 3.

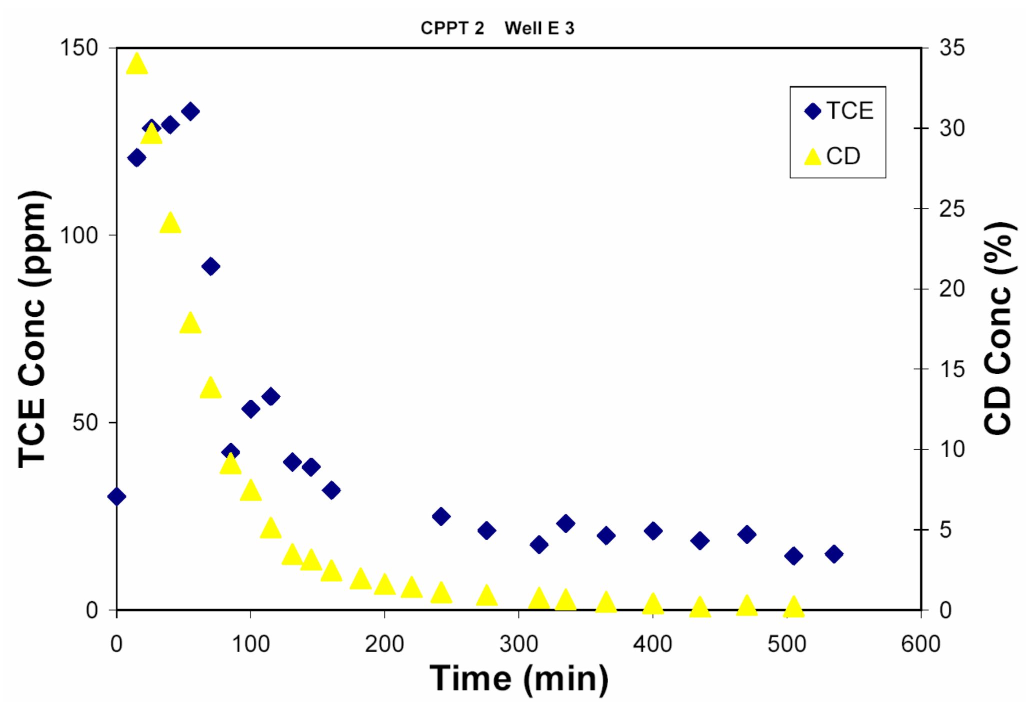



**Figure 5.40:** Comparison of measured TCE and CD concentration during single well CPPT-2 tests on well E 3.

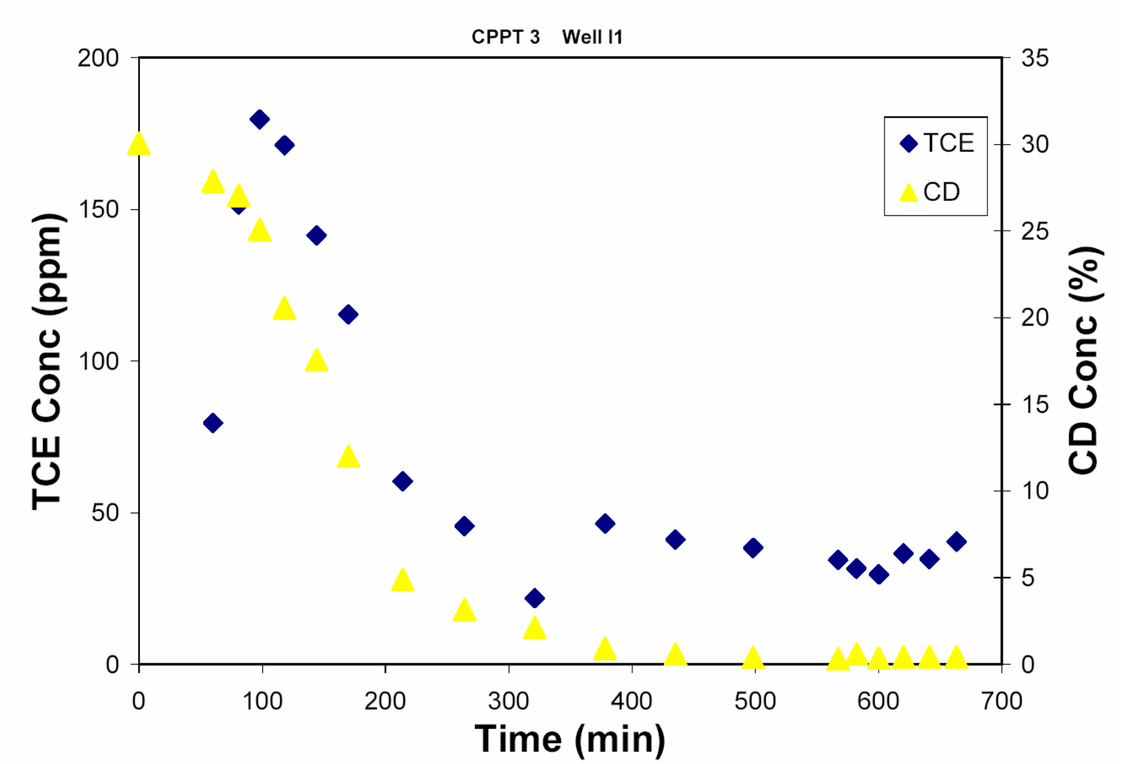



**Figure 5.41:** Comparison of measured TCE and CD concentration during single well CPPT-3 tests on well I1.

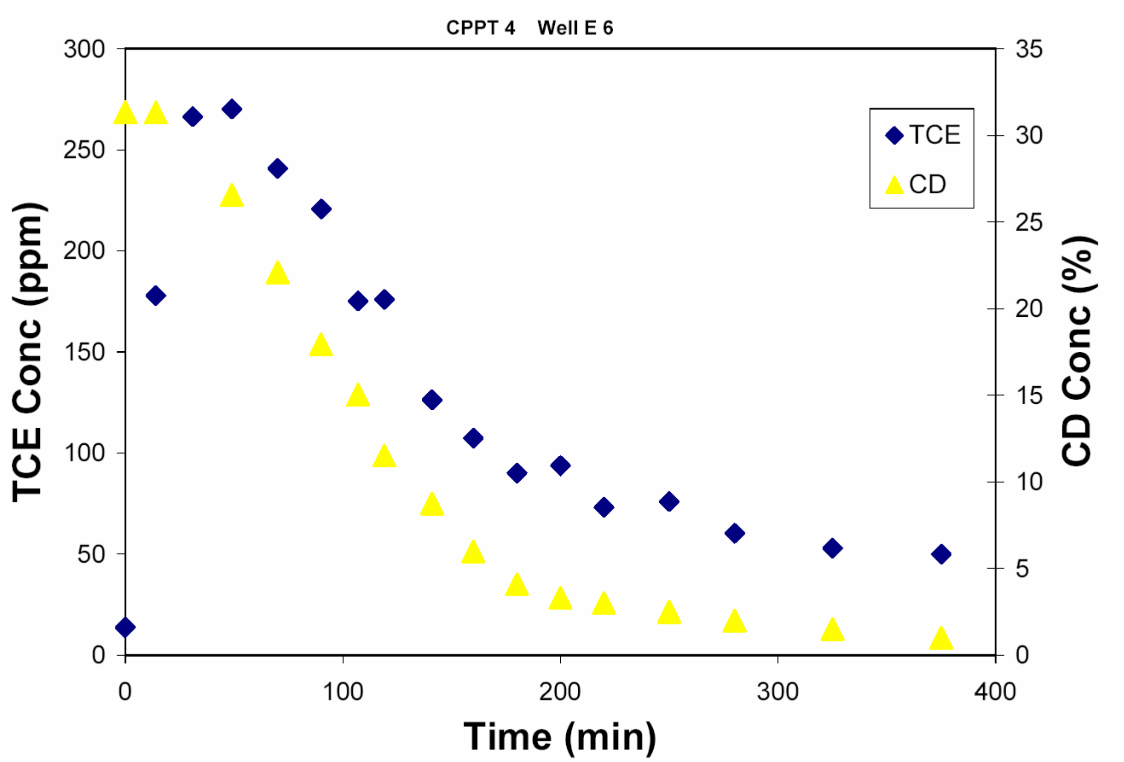



**Figure 5.42:** Comparison of measured TCE and CD concentration during single well CPPT-4 tests on well E 6.

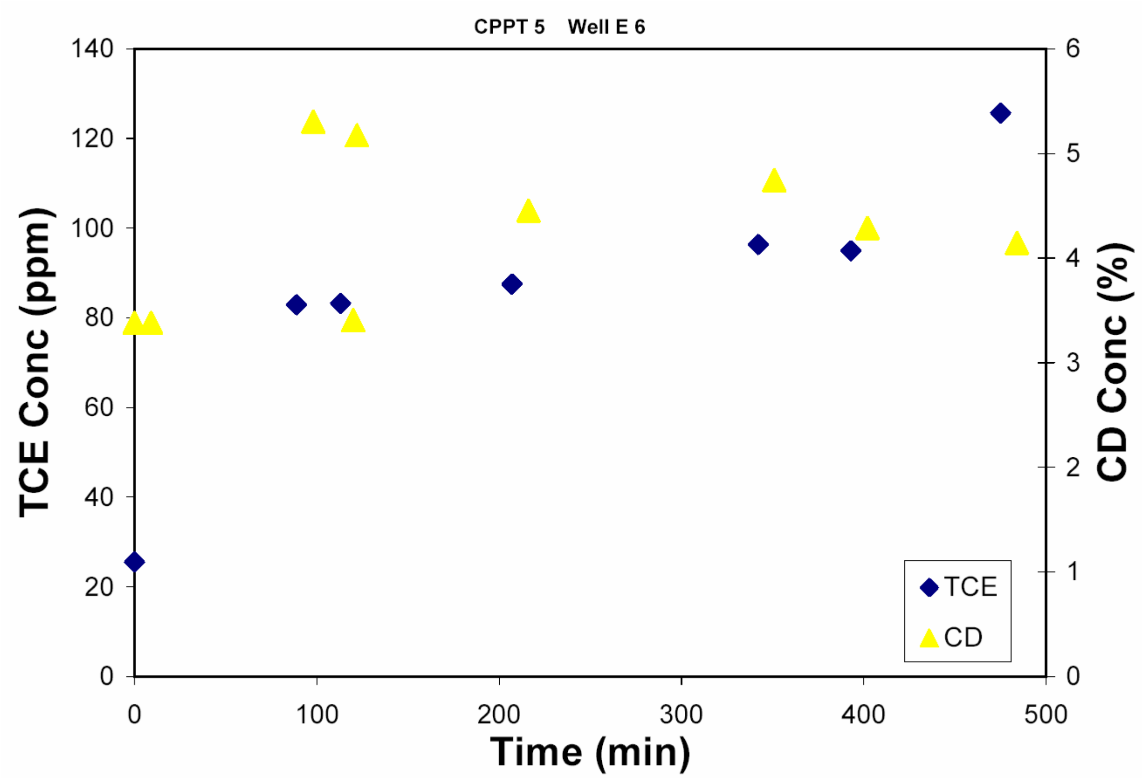



**Figure 5.43:** Comparison of measured TCE and CD concentration during single well CPPT-5 tests on well E 6.

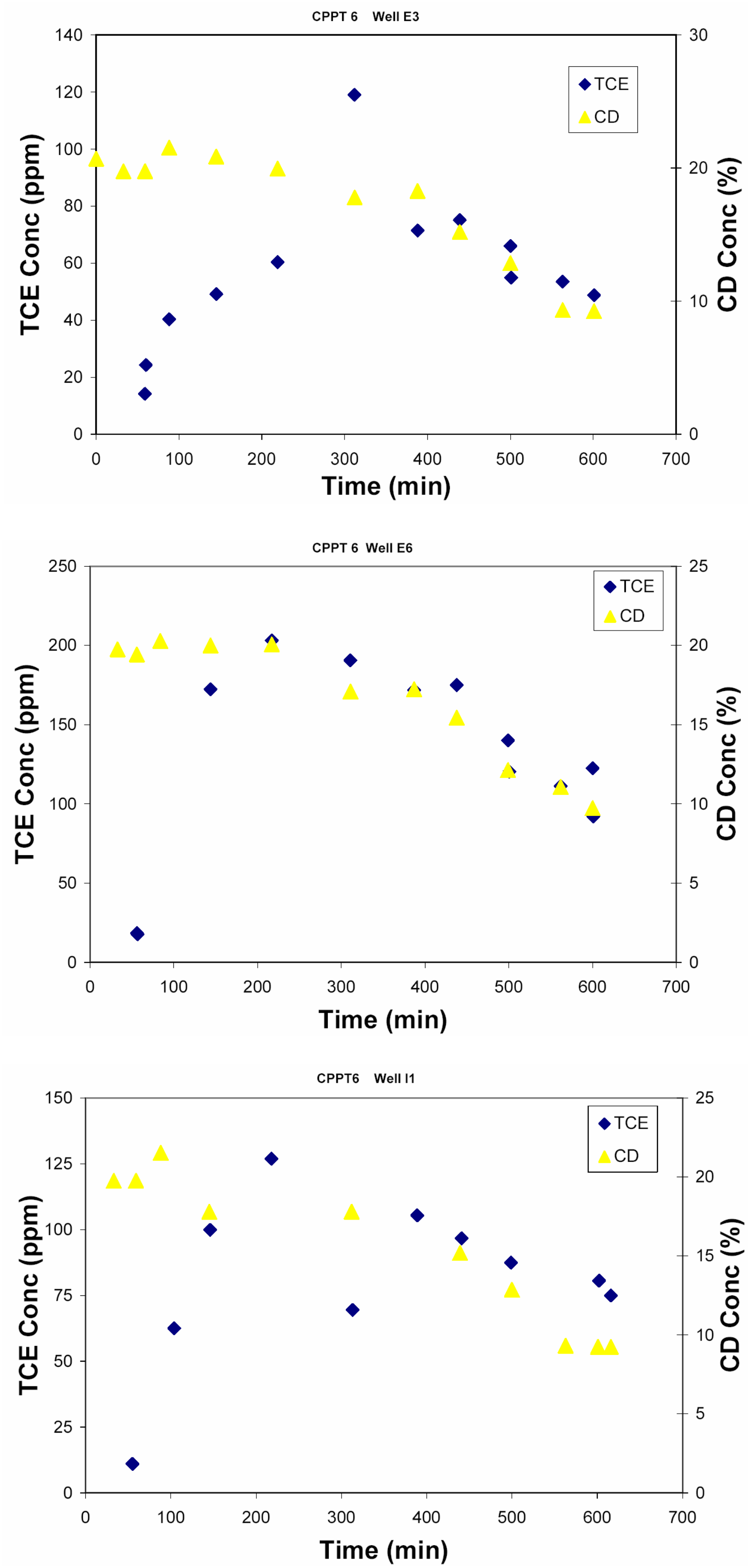
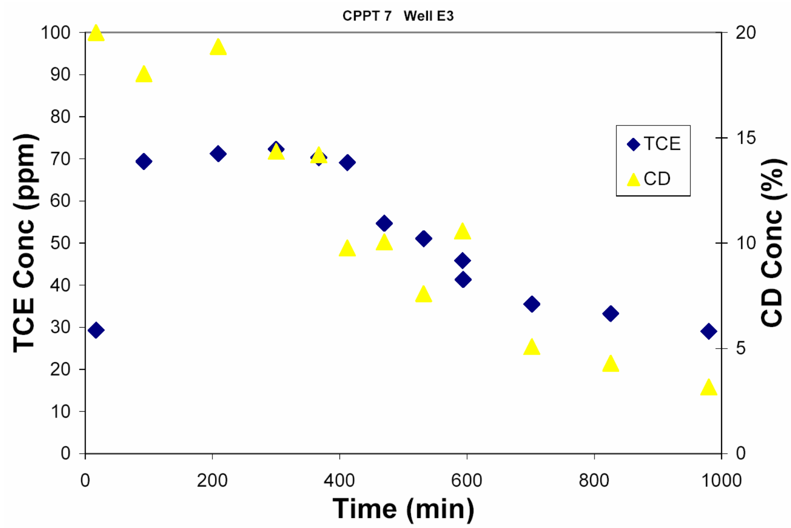
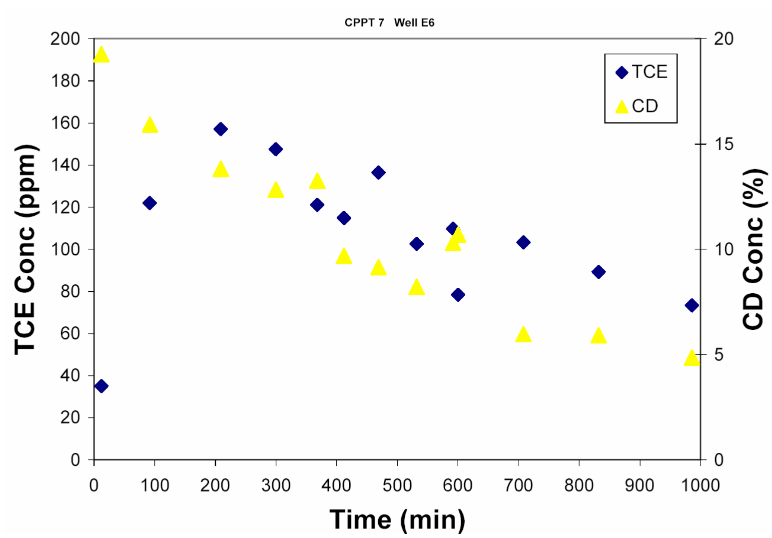



**Figure 5.44:** Comparison of measured TCE and CD concentration during multi-well CPPT-6 tests on well E 3, E6, and I1 (from top to bottom).



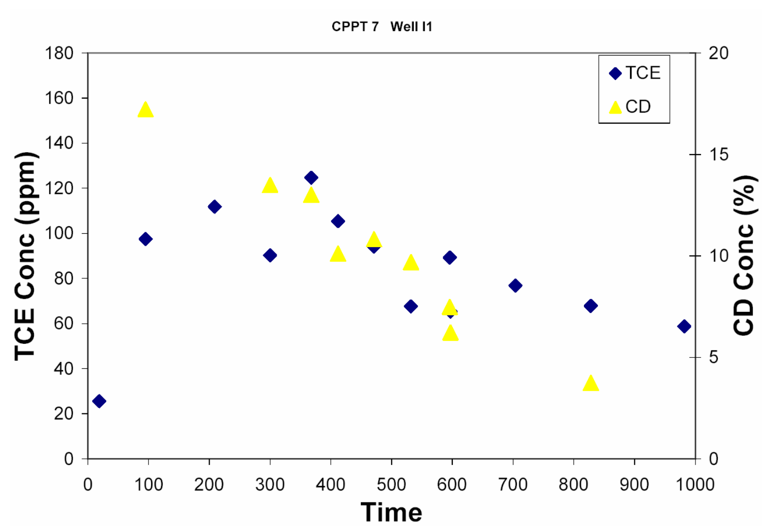




**Figure 5.45:** Comparison of measured TCE and CD concentration during multi-well CPPT-7 tests on well E 3, E6, and I1 (from top to bottom).

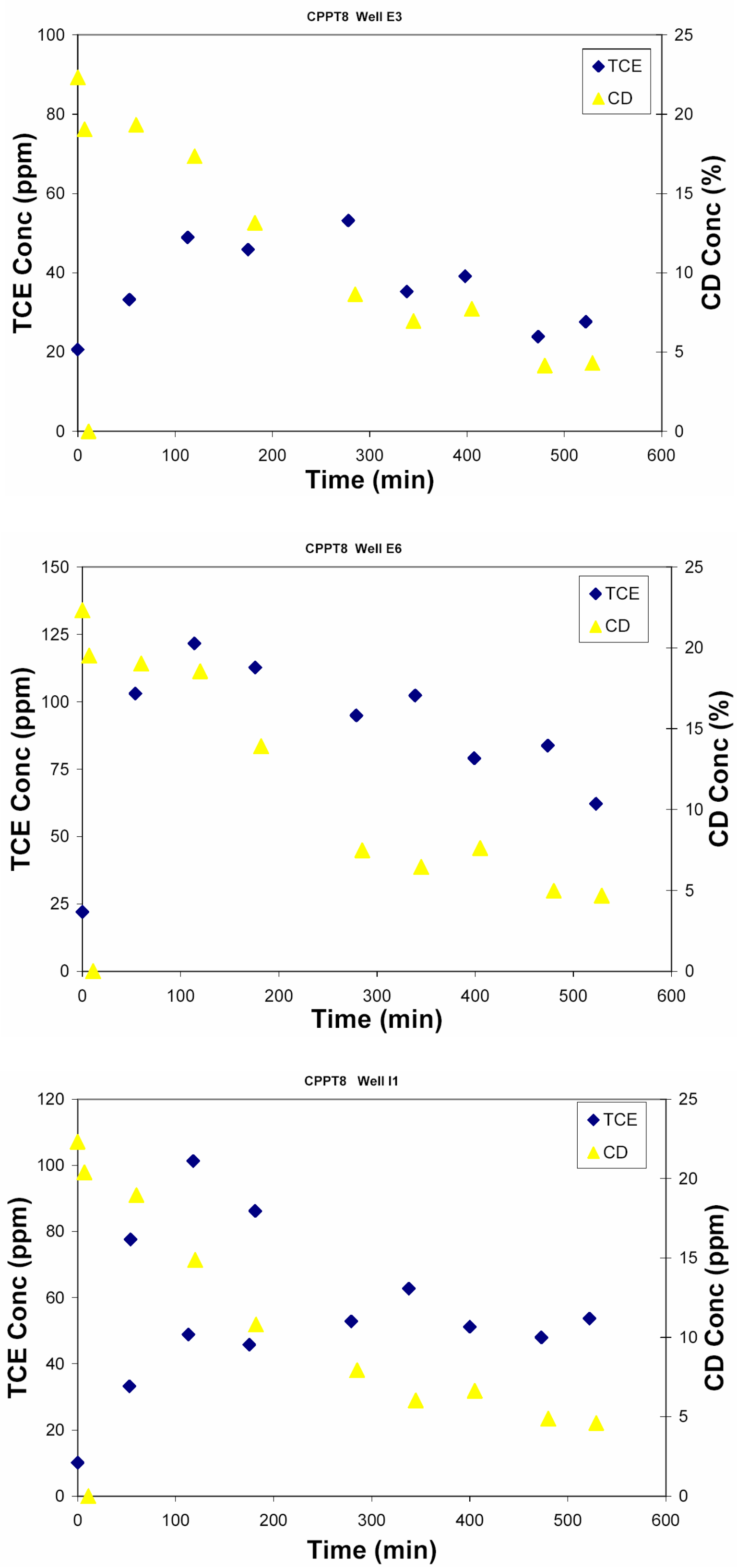



**Figure 5.46:** Comparison of measured TCE and CD concentration during multi-well CPPT-8 tests on well E 3, E6, and I1 (from top to bottom).

The following is a comparison of the expected to the actual quantitative and qualitative performance objectives applying to this part of the demonstration (see Table 4.1).

During the eight CPPT tests 7,430 g (5.3 liter) of VOC were removed (see Table 5.10). Based on the same extraction volume, only 2,072 g of VOC (theoretically) would have been removed using a conventional P&T system. These numbers indicate an extraction volume-based mass removal performance enhancement of 358%. Based on the PTT results, the DNAPL volume recovered during all CPPTs contributed 17.7% of the overall DNAPL removed during this demonstration – 13.6% of which can be attributed to the three multi-well CPPTs alone. About 1.9 times more VOC was removed during the CPPT tests compared to the I/E test (3,995 g or 2.85 L; see Table 5.8). The contribution of the I/E test to the overall DNAPL removal was about 10%.

The performance of CDEF and P&T can also be compared on extraction *time* basis. For example, during the three multi well CPPTs 4.08 kg (or 2.9 liter) VOC were removed over three days operational time (see Table 5.10). During the same time of PTT's (which, again, serve as the proxi for pump-and-treat performance) 3.6 kg (2.6 liter) VOC were removed. These numbers translate into VOC removal rates of 1.36 kg/d for CPPT and 1.19 kg/d for P&T, respectively. Based on these time-based rates, VOC mass removal was 14% higher when using CDEF technology in a push-pull scheme. Recall that the actual extraction time during a CPPT was only 1/3 of the CPPT test time (i.e., the remaining time was used to inject the CD solution and reconcentrate it after the extraction). Thus, if the effective extraction is used as the bases for comparison of CPPT with P&T, the VOC mass removal is 42% higher.

Based on either the extraction time or volume, these numbers demonstrate that CDEF technology shortens the remediation time and enhances the contaminant mass removal rate. Therefore, the qualitative performance criteria "Faster Remediation" and "Reduction in Contaminant Source" (see Table 4.1) were satisfied.

The CPPT remediation scheme differs from conventional P&T in one important way - time and effort must be spent on injecting the CD flushing solution (push phase). This time must be considered "unproductive" because during injection of the flushing solution no contaminant mass is brought to the surface for treatment. This unproductive time can be minimized by using high feed rates, for example, but most effective is using multiple injection wells. Based on our multi-well CPPTs results, extraction times should exceeded injection times. For example, CPPT 7 and CPPT 8 showed that the highest mass recoveries were obtained when the extraction time was about 1.5 times longer than the injection time. Our multi-well CPPT tests lasted on average 20 hours, including injection and extraction of the flushing solution. The duration of our tests was determined by the size of the injected CD slug (approximately 1 PV) as well as the permeability of the aquifer into which is injected (moderate K). Under these conditions it would have been possible to conduct one CPPT every 24 hours.

Besides the unproductive injection time, flushing with CD solution required extra two storage tanks and transfer pipes to and from the tanks. A 2,500 gal storage tanks was used for storage of the 20 % CD solution before injection, and a 6,500 gal tank was used for storage of the recovered, but diluted CD solution. The CPPT scheme required additional monitoring effort of (1) the injection rate and injectate concentration, (2) switching valves and starting the pumps after injection of the CD flushing solution ended, (3) monitoring of the CD concentration in the extract (end criteria: CD concentration = 10%). The tasks were performed by the system operators without additional support. Because no CD reconcentration with the UF system was attempted during the CPPT tests, no other special equipment or additional manpower was necessary. Therefore, the qualitative performance objective “Ease of Use” (see Table 4.1) was satisfied.

Both, the measured amount of contaminant mass recovered during the CPPT as well as the PTTs indicated a reduction in subsurface contamination. Although the qualitative performance criterion “Reduction in Contaminant Mobility: Smaller Plume” could not be directly correlated to the CPPT test performance because the I/E test also contributed to the remediation, all test combined clearly reduced the contaminant mass in the source zone. The results of the ongoing long term study will demonstrate the overall effect of this demonstration on the plume size. However, with regard to the quantitative performance objectives (see Table 4.1), the VOC mass recovered during the CPPT tests equaled approximately 5.3 liter DNAPL. Based on the PTT estimates of the initial DNAPL saturation, this volume translates in a mass reduction of about 14.3% by CPPT flushing.

During the three multi-well CPPT’s, 3,395 kg CD were injected of which 3,356 kg were recovered. The injected mass of CD includes 1,592 kg worth of 40% CD stock solution that had to be added to readjust the recovered CD flushing solution to the desired injection concentration of 20%. 1,803 kg CD was recovered and recycled. The fraction of reused CD mass during CPPT-7 was 69% and 0.33% during CPPT-8. The overall CD reuse percentage, defined as the ratio of the recycled CD mass injected divided by the total CD mass, was 99%. The planned reuse factor was 5 or higher (see Table 4.1). The failure of the UF system to operate in continuous mode was the main reason for the lower than expected reuse factor. The reuse percentage for the multi-well CPPT system exceeded the I/E application scheme (79%). This difference demonstrated that the CD flushing solution can be more effectively used in a push-pull application scheme.

With regard to “maintenance” and “reliability” criteria defined for this demonstration (see Table 4.1), the operation of the aboveground treatment system was simple and was confined to regular leak checks and flow rate readings. During the CPPT test, no major maintenance of the principal system components (sand filter, air stripper, and air activated carbon filter) was required. The sandfilter was still fully functioning when the CPPT tests were terminated. The amount of iron precipitate that collected inside the air stripper did not influence the performance of the unit. In response to very high contaminant concentrations, up to two water activated carbon filter had to be added to the treatment train to polish water designated for discharge into the storm drain. The necessary effort to place these filters in-line was minimal and the work was conducted within “regular” CPPT operating hours. Overall, the aboveground and below ground equipment proved to be robust, easy to operate, and required little maintenance or repair.

At least during the demonstration period, the performance criteria defined for "maintenance" and "reliability" were satisfied.

The operation of CDEF in push-pull mode had several major advantages over the I/E test. First, the aboveground treatment system can be taken off-line during injection times. Again, the optimal ratio of injection time to extraction time was 1.5. Thus, for every three hours of extraction time, there were about 2 hours time for maintenance and repairs. During this demonstration, this would have been ample time to respond to any problems.

The second advantage of the multi-well CPPT over the I/E test was that anaerobic conditions were maintained during the entire operation without significant modification of the treatment system. Recall that during the I/E test, well clogging was caused by iron precipitation in the injection wells. The source of the iron precipitates originated in the air stripper, where the extracted solution was aerated immediately before reinjection. The aerobic solution leaving the air stripper contained suspended iron precipitates that enter and clogged the injection wells. During the CPPT, the extracted flushing solution also passed through the air stripper, but was then stored in a 6,500 gal tank until the next CPPT test. The storage time during the multi-well CPPTs lasted from 2 to 4 days. During the storage time, the naturally occurring degradation of the CD consumed most of the dissolved oxygen and caused the solution to become anaerobic again. The lowest DO concentrations were measured at the bottom of the storage tank. Because the storage tank outlet was also at the bottom of the tank, the solution that was reinjected during the multi-well CPPTs was anaerobic. In addition, any iron minerals that made it into the storage tank (or formed at the interface between the solution and the atmosphere) had sufficient time to settle inside the tank. Further, the storage tank was sealed to minimize contact of the stored flushing solution with the atmosphere.

The third advantage is that by terminating the extraction when CD concentrations are still high (5% to 10% wt/wt), the slug of fresh 20% CD flushing solution injected during the following CPPT experiences less dilution if injected into water with no CD. Thus, as demonstrated by the multi-well CPPTs, higher CD recoveries and less CD mass consumption is possible.

The CPPT's were performed over more than 3 weeks, but could have been completed (theoretically) within 5 days of semi-continuous treatment (i.e., alternation of injection and extraction). All CPPT test combined produced 54.84 $m^3$, of which 27.7 $m^3$ resulted from the three multi-well CPPT's. The average flow rate was 10.9 $m^3$ per day (2,900 gpd). Compared to the per day flow rate achieved during I/E test, about 20% more water was extracted during the CPPT tests. The demonstration plan provided for a treatment capacity of one PV per day. The actual treatment capacity realized during the CPPT tests was 1.2 PV per day. Based on this measure, the performance criterion was met.

The CD concentration in the extracted water during the multi-well CPPT tests was about 10 % or higher (see Figure 5.13), which exceeded the expected performance criterion (see Table 4.1). In contrast to the I/E test, hydraulic control over the injection/extraction field was much easier to achieve. The main reason for this was the absence of well clogging which led to lower injection rates during the I/E test.

The DO content of the subsurface water remained below than 5% during the multi –well CPPT test. Although the relative fast onset of CD degradation in the field was not expected from prior lab studies, the low DO content did not affect the performance of the CDEF, i.e. there was no evidence that the degradation rate of the CD was fast enough to result in significant CD mass loss. Conversely, the degradation of the CD may have the added benefit of facilitating the (bio) remediation of the VOC present at the site. It is expected that the results of the long term CD fate study will provide evidence that this contaminant degradation process was initiated by adding CD.

The other factors listed in Table 4.1 were encountered as expected or did not influence the demonstration performance.

### 5.4 Performance of CDEF in comparison to P&T

The results obtained during this CDEF demonstration were compared with conventional P&T, which still remains the most commonly implemented remediation strategy. The basis of the comparison were the detected average TCE and 1,1,1-TCA concentrations during both PTTs (see Section 4). Again, using the PTT concentration almost certainly resulted in an overestimation of the P&T efficiency. This conservative performance assessment approach therefore provides a solid data base for comparison of P&T and CDEF technology.

Figure 5.47 shows the solubility enhancements for TCE and 1,1,1-TCA at each of the three test wells as observed during all CDEF tests (CPPT and I/E application schemes). The enhancement was determined by dividing the total TCE or 1,1,1-TCA mass removed during a test by the total mass of compound that would have been removed during a (theoretical) P&T. Thus, a value of "one" indicates no removal enhancement, while any number >1 indicates that the removal was greater than what would have been possible using P&T technology. The tests shown in these figures were arranged in the order they were conducted. The first five CPPT tests were single-well tests, while CPPT-6 through CPPT-8 were multi-well tests. The injection/extraction test, IE, was conducted before these multi-well tests. The data set used to generate Figure 5.47 is tabulated in Table 5.11.

Figure 5.47 reveals several important findings. First, the contaminant removal was enhanced during all CDEF tests, which underlines that CDEF remediation is working under field conditions. Second, the enhancements systematically changed with time (i.e., from test to following test). These changes were particularly visible at well E6. Here, 1,1,1-TCA removal efficiencies were similar during CPPT-4 and CPPT-5 and the following the I/E tests (~19 times enhancement). The, the removal efficiency dropped in a near linear fashion until it reached 9.8 after CPPT-8. This trend, if it continued, indicates that 3 to 4 additional CPPT tests would have been possible before the effectiveness of the CPPT reached that of P&T. Similar results were obtained for TCE and the wells E3 and I1.

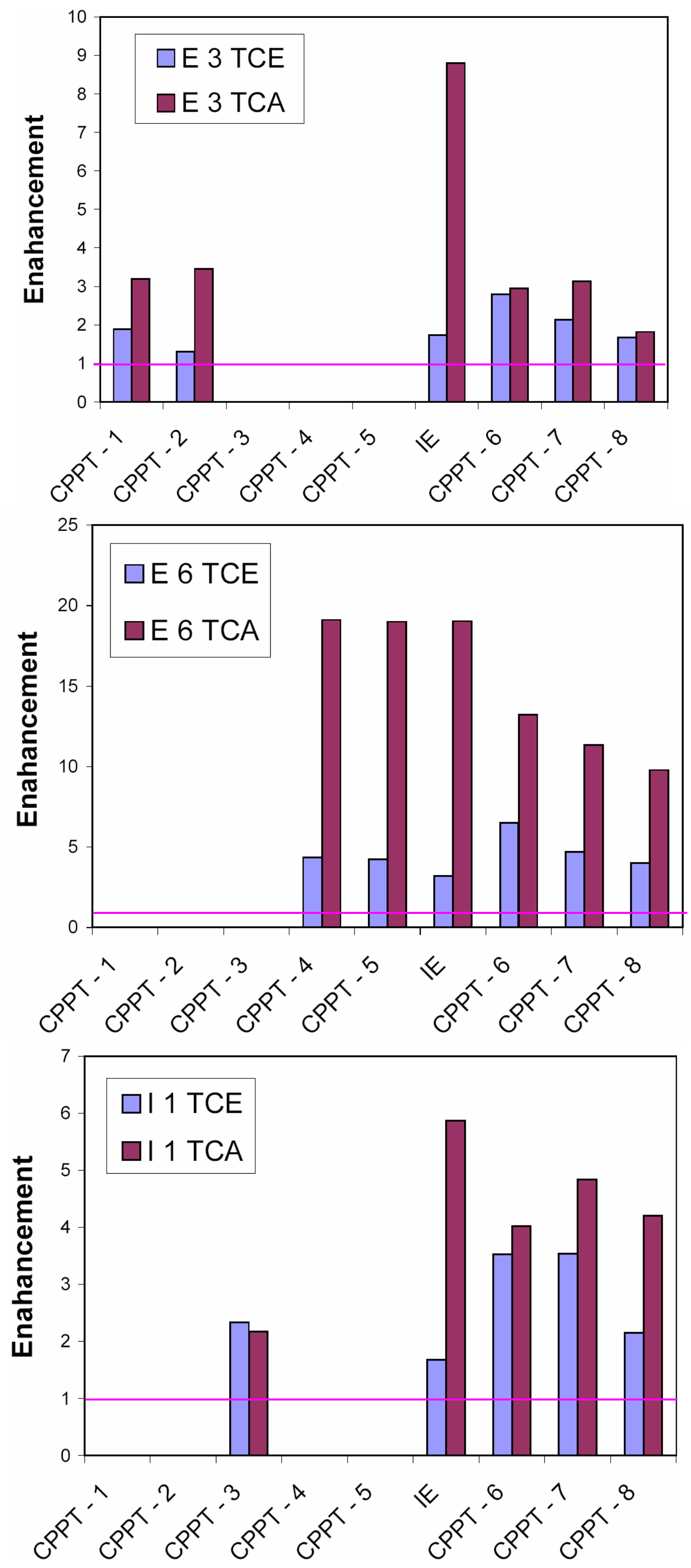



**Figure 5.47:** The measured solubility enhancements for TCE and 1,1,1-TCA at each of the three test wells as observed during all CDEF tests (CPPT and I/E application schemes). Pink line indicates (theoretical) performance of a P&T system.

The third important finding was that the observed solubility enhancements were different for TCE and 1,1,1-TCA. In case of TCE, they ranged from 1.3 to 6.5 for TCE and were even higher for 1,1,1-TCA, ranging from 1.8 to 19.1. The favored removal of 1,1,1-TCA came as a surprise because from pre-demonstration site investigations it appeared the TCE was the main contaminant. TCE and 1,1,1-TCA have similar solubilities (~ 1,100 mg/L) and similar densities (~1.4 g/cm$^3$), they should have seen similar solubility enhancements in CD solution. Raoult's law is commonly used to explain dissolution from mixtures of NAPLs. The law states that the apparent solubility of a compound is dependent on the aqueous solubility of the compound times its mole fraction in the NAPL source. If 1,1,1-TCA made up a higher fraction of the DNAPL mixture than TCE, then Raoult's law dictates that 1,1,1-TCA should dissolved preferentially. Thus, our findings provide evidence that the DNAPL in the source zone at Site 11 is less TCE rich than previously thought.

| Test ID | Well ID | TCE | 1,1,1-TCA |
|---|---|---|---|
| CPPT - 1 | I1 | NT | NT |
| CPPT - 2 | I1 | NT | NT |
| CPPT - 3 | I1 | 2.3 | 2.2 |
| CPPT - 4 | I1 | NT | NT |
| CPPT - 5 | I1 | NT | NT |
| IE | I1 | 1.7 | 5.9 |
| CPPT - 6 | I1 | 3.5 | 4.0 |
| CPPT - 7 | I1 | 3.5 | 4.8 |
| CPPT - 8 | I1 | 2.2 | 4.2 |
| | | | |
| CPPT - 1 | E6 | NT | NT |
| CPPT - 2 | E6 | NT | NT |
| CPPT - 3 | E6 | NT | NT |
| CPPT - 4 | E6 | 4.3 | 19.1 |
| CPPT - 5 | E6 | 4.3 | 19.0 |
| IE | E6 | 3.2 | 19.0 |
| CPPT - 6 | E6 | 6.5 | 13.2 |
| CPPT - 7 | E6 | 4.7 | 11.4 |
| CPPT - 8 | E6 | 4.0 | 9.8 |
| | | | |
| CPPT - 1 | E3 | 1.9 | 3.2 |
| CPPT - 2 | E3 | 1.3 | 3.5 |
| CPPT - 3 | E3 | NT | NT |
| CPPT - 4 | E3 | NT | NT |
| CPPT - 5 | E3 | NT | NT |
| IE | E3 | 1.7 | 8.8 |
| CPPT - 6 | E3 | 2.8 | 3.0 |
| CPPT - 7 | E3 | 2.1 | 3.1 |
| CPPT - 8 | E3 | 1.7 | 1.8 |

**Table 5.11:** Removal efficiencies of all CDEF tests (CPPT and I/E). The values represent the solubility enhancement in the presence of CD compared to flushing without CD (i.e. pump-and-treat), NT = not tested.

Table 5.12 provides an overview of the overall mass balance yielding the ~30 liter DNAPL removal estimate cited in the report (assuming all VOC removed was DNAPL). The DNAPL volume removed during the each test was calculated from the contaminant concentrations measured during each test that was conducted at Site 11. Table 5.12 also provides an estimate of the DNAPL mass remaining after each test. The initial DNAPL volume (ca. 38 l) was determined on the basis of the pre-test partition tracer test. As shown in Section 5.2, the calculated initial DNAPL saturation was $S_n$ = 0.67% (however, as noted in this report, there is notable uncertainty regarding this estimate). Based on the post-PTT, the DNAPL saturation declined by ~80% at the end of the demonstration (see Section 5.2). It was assumed that the change in DNAPL saturation was caused by the measured removal of ~30 liters DNAPL. Because of the problems interpreting the PTTs results (see Section 5.2) this is the best working estimate and the actual DNAPL volume (initial and final) could be somewhat higher or lower. Table 5.12 shows that during all CDEF tests (I/E and CPPT's) about 29% of all recovered DNAPL was removed, while the remainder was flushed out during the PTTs and other tests. This seemingly disproportional low performance of CDEF was caused by the comparably short operational time of the CDEF technology. However, as shown in Table 5.13, the CDEF technology removed DNAPL mass much more efficiently when in operation.

| Test or Activity | VOC Mass removed (g) | DNAPL Volume removed[1] (liter) | Percentage of DNAPL mass removed during demonstration [2] (%) | Percentage of DNAPL remaining in subsurface [3] (%) |
|---|---|---|---|---|
| Pre-test PTT | 14,434 | 10.3 | 35 | 73 |
| Hydraulic test and other[4] | 5,880 | 4.2 | 14 | 61 |
| I/E test | 3,995 | 2.9 | 10 | 53 |
| CPPT single-well tests | 3,555 | 2.6 | 9 | 46 |
| CPPT multi-well tests | 4,076 | 2.9 | 10 | 38 |
| Post-test PTT | 9,377 | 6.7 | 22 | 20 |
| **TOTAL** | **38,517** | **29.6** | **100** | **20** |

[1] Assumes all VOCs were DNAPL

[2] Based on the volume of DNAPL (ca. 30 l) removed during all site activities.

[3] Based on the initial DNAPL volume present at the site before begin of this demonstration (ca. 38 l). The initial DNAPL volume was determined on PTT analysis (best estimate).

[4] Best estimate. Sample frequency during hydraulic tests was lower than during CDEF and PTT tests.

**Table 5.12:** Overall mass balance yielding the approximate 30 L removal estimate cited in the report, as well as the estimated mass remaining after all testing.

Table 5.13 provides a comparison of the VOC-DNAPL masses removed during the CDEF demonstration and compares them to conventional P&T. The basis of for calculating the P&T performance was again the average contaminant concentration measured during the PTTs. The per-day mass removal rates for the P&T were based on flushing 1 PV (ca. 9,000 liter) per day. This treatment volume was similar to the average extraction rates during the CPPT tests (see section 5.3.2) and only slightly higher than during the I/E test (see Section 5.3.1).

| Type of Remediation Scheme | TCE and VOC mass removed | | | | | |
|---|---|---|---|---|---|---|
| | per 1000 gal flushed | | per kg CD used | | per day of operation | |
| | TCE (g) | VOC (g) | TCE (g) | VOC (g) | TCE (g) | VOC (g) |
| Injection/extraction (I/E) | 144 | 280 | 1.1 | 2.1 | 294 | 571 |
| Push-pull (CPPT) | 304 | 524 | 0.9 | 1.6 | 740 | 1276 |
| Pump -and-Treat (P&T) | 90 | 183 | NA | NA | 213 | 434 |

**Table 5.13:** Comparison of I/E and CPPT treatment schemes to (theoretical) P&T.

Table 5.13 shows that both CDEF application schemes outperformed the P&T approach. The best performance was reached during the CPPT test. For example, the CPPT tests showed 338% higher TCE removal rates on a per 1000 gal flushing basis. On a per day comparison basis, about 3.5 times more TCE was removed. Again, by using the contaminant concentrations obtained during the PTTs as a measure for the performance of a theoretical P&T system at Site 11, the performance of the P&T is most likely overestimated. Thus, the CDEF performance parameter provided in Table 5.x should be viewed as conservative estimates, while the actual performance should be somewhat higher.

### 5.5. Performance of the Membrane Systems

The membrane systems used during the CDEF demonstration at Site 11 were rented from MTR Membrane Technology Research Inc., Menlo Park, CA. The first membrane system consisted of an ultrafiltration, UF, filter for the reconcentration of extracted CD flushing solution. The second system was a pervaporation, PVP, unit that was tested as treatment alternative to air stripping. The following is a discussion of the performance of these systems under field conditions.

#### 5.5.1. Performance of the UF System

The UF system was initially run in batch. Samples were obtained from inside the 150 gal feed tank that was part of the UF system. Pictures of the UF system are included in Appendix III. Samples taken during the UF test were analyzed primarily for CD concentration, although VOC was analyzed in selected samples. The feed that was used during the batch UF test was CD solution extracted from wells E3, E6, or I1. Before processing the extract in the UF system, it was passed through the pervaporation unit and then for the air stripper to remove any VOC leftovers. The solution that entered the UF system had an HPCD concentration of approximately 5% (wt/wt) and TCE content lower than 1 mg/L.

During the batch mode, the UF system tank was fed with 475 gallons extracted CD flushing solution. As it can be seen in Figures 5.48 and 5.49, the feed concentration increased from 5% to more than 10% while the CD concentration in the permeate stream decreased from 5% to less than 3%. The increase of the CD concentration in the feed stream was a consequence of continuous water removal from the batch. On the other hand, the constant decrease in the HPCD concentration in the permeate stream was a consequence of the stabilization of the UF process and the formation of an CD layer on the membrane surface. This layer formation (cake) became more compacted along with time, permitting an easier blocking of the CD. The UF permeate was discarded and the rejectate, CD rich solution was recirculated through the treatment zone.

During this particular UF batch operation, the CD concentration in the feed tank was doubled in a period of seven hours. The initial permeate flowrate was 2 gpm, but declined to 0.5 gpm at the end of the test. The permeate flowrate decreased in response to increasing transmembrane pressure. The operating transmembrane pressure was specified not to exceed 13 psi. The pressure was maintained at this pressure manually adjusting a bypass valve that communicated the feed stream with the storage tank.

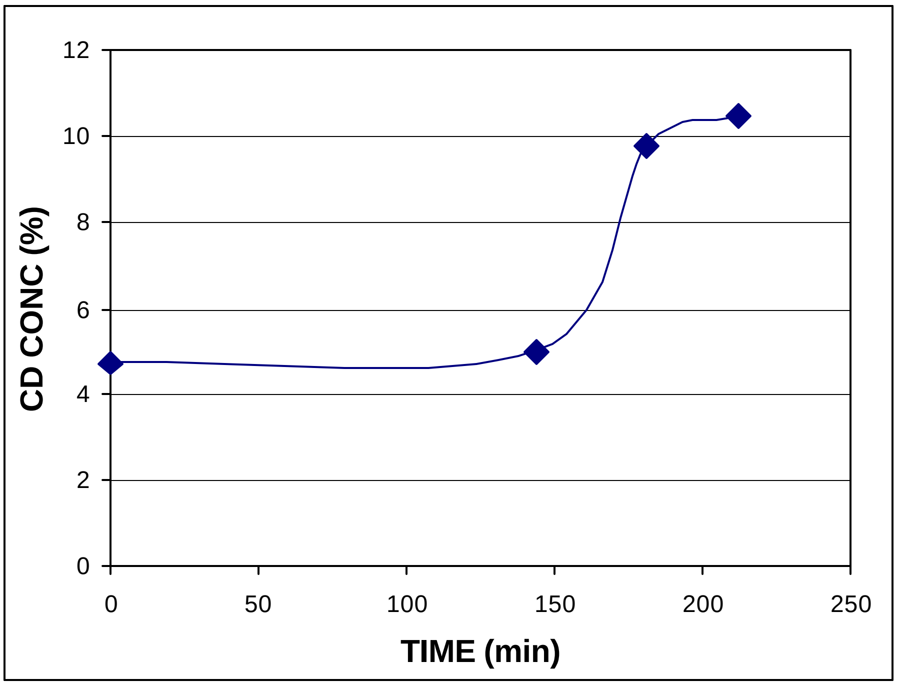



**Figure 5.48**: Results of operating the UF system in batch mode: CD concentration of the feed with time

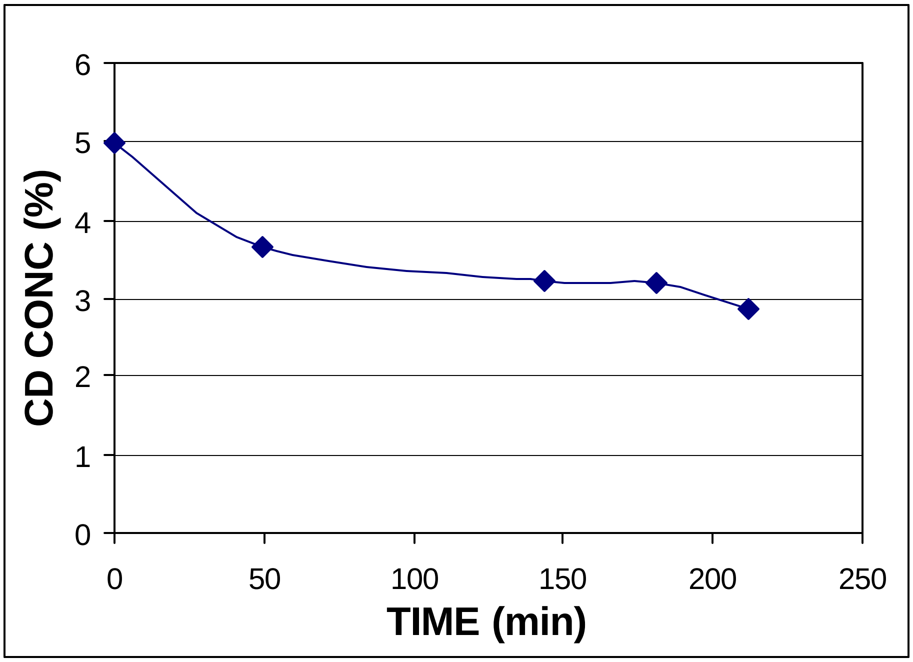



**Figure 5.49:** Results of operating the UF system in batch mode: CD concentration of permeate with time

Figure 5.50 shows the result of another UF batch test. The initial feed concentration during this test was 10.6 %, while the ultimate CD concentration was 22.2%. During the UF process, the volume of the CD solution was reduced from 150 gal to a little over 70 gal (volume was determined by reading tank gradation). 150 gal of 10.6% CD were equal to 60.1 kg CD, whereas 70 gal of 22.2% CD solution equaled 58.7 kg. Thus, during the UF process, less than 3% of the CD mass had been lost in the permeate stream. The performance criterion for a successful UF application was that the CD flushing solution can be reconcentrated to 20% and that the reconcentration had to be 80% effective. While these criteria were met, it took about 24 hours for the UF system to reach the desired concentration.

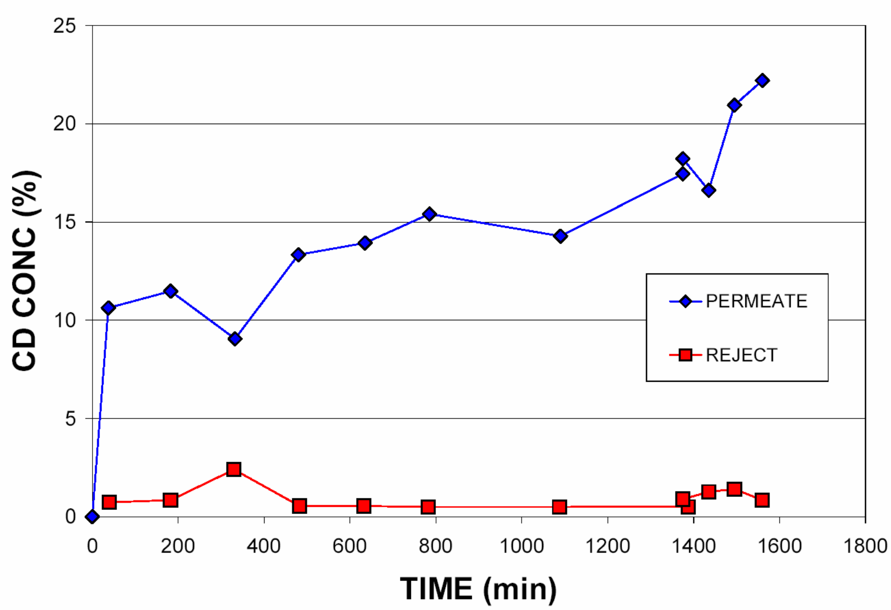



**Figure 5.50:** Result of operating the UF system in continuous mode. For this test, the initial CD feed concentration was 10.6%. The ultimate CD concentration reached was 22.2 %:

A second set of tests of the UF system were carried out in continuous operation mode. During these tests, samples were collected from three sample locations: (1) feed, (2) rejectate stream and (3) permeate stream. The feed into the UF was treated for VOC in the air stripper and the pervaporation unit. The feed was flushing solution recovered form wells E3, E6, and I1. The feed stream had an average CD concentration of 5 % and TCE content lower than 1ppm. During these tests, the rejectate was fed back into the CDEF flushing system for reuse, while the permeate was discharged.

Figures 5.51 through 5.54 summarize the results of one particular UF test. As can be seen in Figure 5.51, the permeate concentration was almost stable at all times. On the other hand, the permeate CD concentration did decrease along time as a consequence of a hydrodynamic layer (cake) formation by the rejected CD on the membrane's surface (see Figure 5.52). This caking phenomenon was observed also during the batch mode operation. In Figure 5.52 it can be seen how the rejection increased with time. Figure 5.53 shows that the flow rates decreased with time in response to the caking, while during the same time the CD rejection increased. Thus, the CD rejection was inversely proportional to the flow rates of both the feed and permeate stream. The formation of a layer increased the general resistance of the system to permeation and resulted in decreasing treatment rates. The CD concentration in the rejectate and permeate at the end of the test were approximately 8% and 1%, respectively. Based on the ratio of the feed CD concentration (5%) and rejectate concentration (8%), the CD recovery during continuous mode operation was approximately 68% effective.

Despite the UF system was effective in re-concentrating/recovering the CD from the extracted flushing solution, its recovery rate as a function of time was not. The design specifications provided for an operating flow rate of 5 gpm, which would have been necessary to run the UF system in continuous mode and allow continuous CD reconcentration during CDEF was 4 gpm to 5 gpm. The actual flowrate achieved during testing the UF system ranged from 0.5 gpm to maximum 2 gpm. Better re-concentration rates would have been achieved by using a larger membrane area. However, a system upgrade was not delivered in time to be tested during the demonstration. For this reason, the UF could not be used during the CDEF demonstration.

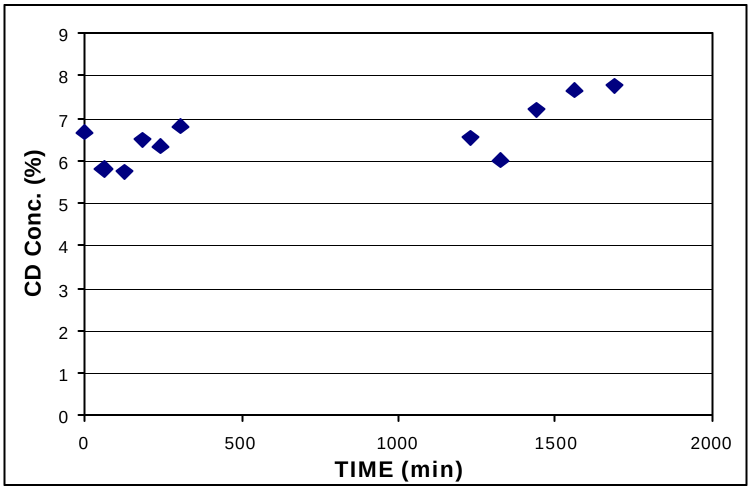



**Figure 5.51:** Results of operating the UF system in continuous mode: CD concentration of the rejectate with time

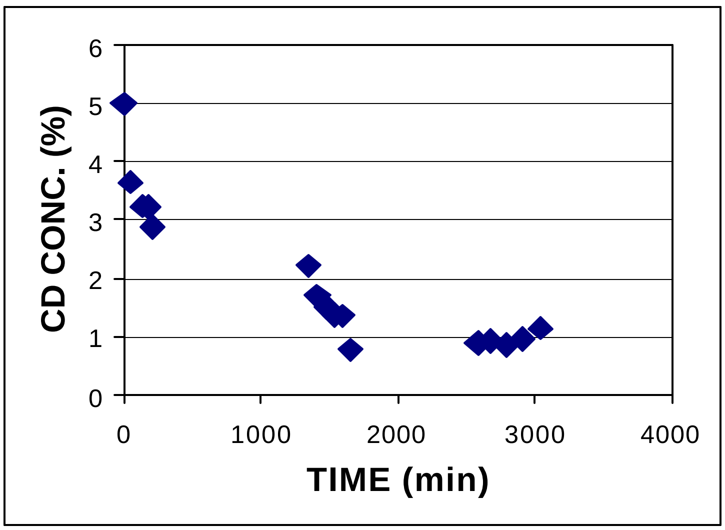



**Figure 5.52:** Results of operating the UF system in continuous mode: CD concentration of the permeate with time

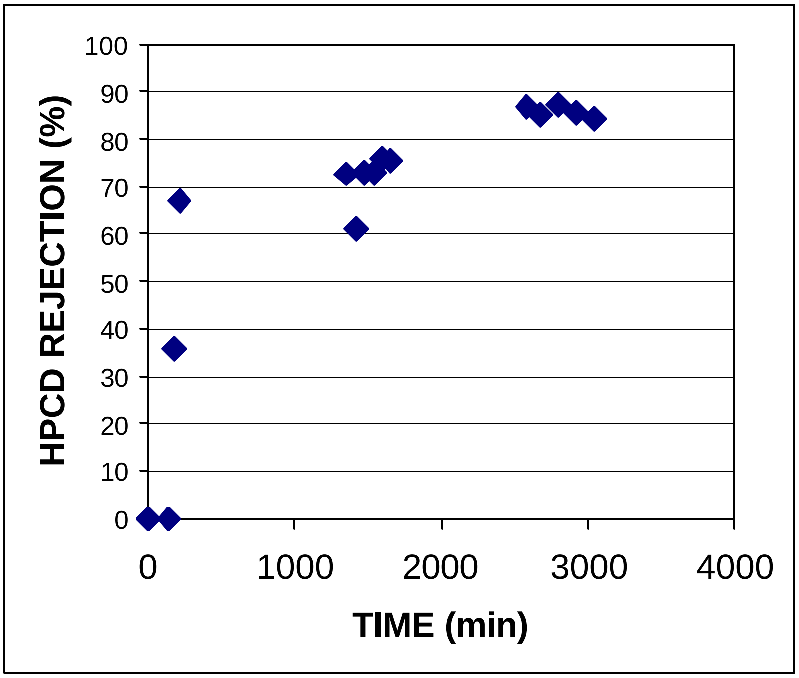



**Figure 5.53**. Results of operating the UF system in continuous mode: CD Rejection with time

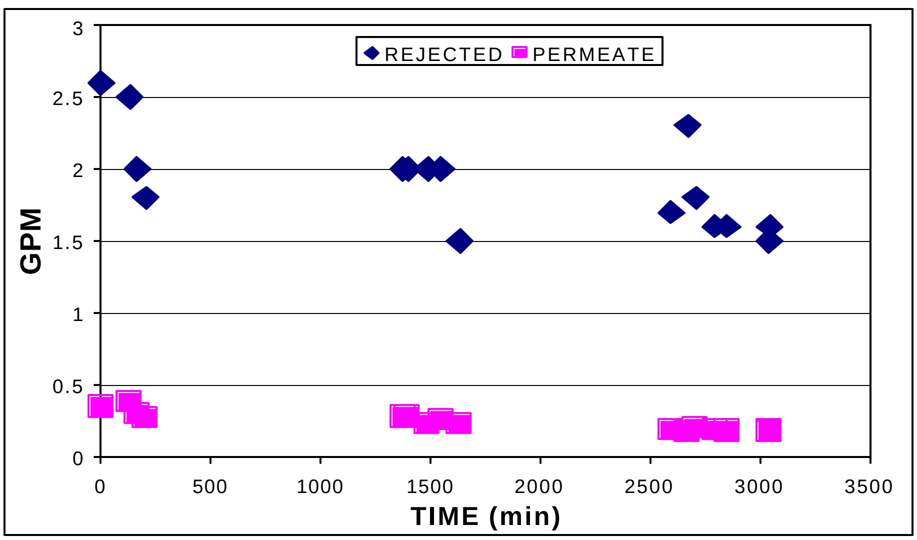



**Figure 5.54.** Results of operating the UF system in continuous mode: Volumetric flow rates of the feed and permeate

### 5.5.2. Performance of the PVP System and the Air Stripper

Pictures of the PVP system are included in Appendix III. The PVP system for the treatment of VOCs in the CDEF effluent was damaged during setup. A service technician was brought to the site, but was not able to repair all the damage in the field. Because of that the PVP never reached its designed treatment capacity of 5 gpm and was never operated in continuous mode. In consequence, only a few of the planned performance tests could be carried out.

For a series of test, the PVP was operated in batch mode. The sample locations included the feed, the VOC enriched permeate, and the rejectate. The feed for the PVP tests was extracted from wells E3, E6, and I1. Contaminant concentration in the feed ranged from 3.9 mg/L to 47.9 mg/L TCE and 3.4 mg/L to 47.5 mg/L 1,1,1-TCA. The treated rejectate showed TCE concentration ranging from below detection limit to 2.8 mg/L and 1,1,1-TCA concentration from below detection limit to 2.7 mg/L. The presence of any detectable VOC in the rejectate was closely linked to the feed concentration, i.e., the lowest rejectate concentration were measured when the feed concentration were low. The contaminant enriched permeate leaving the PVP showed contaminant concentration as high as 111.7 mg/L TCE and 78.68 mg/L 1,1,1-TCA. As for the rejectate concentration, the highest permeate VOC concentrations were observed during treatment of high feed concentration.

| | **REMOVAL** | | |
|---|---|---|---|
| | 1,1-DCE | 1,1,1-TCA | TCE |
| Pervap | >99% | >99% | 94.1 |
| | **VOLUME REDUCTION** | | |
| | DCE | 1,1,1-TCA | TCE |
| Pervap | 3.90 | 1.66 | 2.33 |

**Table 5.14**. TCE, 1,1-DCE and 1,1,1-TCA removal percentages determined for the PVP system. Also shown are the achieved volume reductions during PVP operation. The 1,1-DCE measurements were affected by peak interference and must be considered best estimates only.

Table 5.14 summarizes the average contaminant mass removal and volume reduction percentages determined during all PVP test. The volume reduction was calculated based on the ratio of feed volume and permeate volume and the corresponding masses of contaminants dissolved in those solutions. For example, the volume reduction rate for TCE was 2.33. This means that 2.33 times more TCE was enriched in the permeate compared to the feed. The results of these limited PVP test support the effectiveness of the pervaporation system. The pervaporation unit achieved VOC removals of compounds such as TCE, 1,1-DCE and 1,1,1-TCA above 90%. The chemical analysis of 1,1-DCE was influenced by peak interference of an unidentified compound (see section 4.7). However, because all of the analyzed solution processed by the PVP were subject to this interference, it was assumed that the observed changes in 1,1-DCE concentration were due to the PVP process. The volume reduction of each compound was at least twice the initial concentration. Especially it was not possible to assess the PVP under continuous mode operation, the data set provided in this section was to limited to provide a more conclusive performance evaluation of the PVP technology.

*Air stripper performance*: The treatment performance of the air stripper was determined during all stages of the demonstration. Picture of the air stripper a provided in Appendix III. These test included sampling of the feed and the air stripper effluent. After initial test, the removal performance was at 82.2%. A system upgrade (i.e. a second stripper tray) was provided by IEG Technology INC from which the air stripper was purchased. After installation of the system upgrade, the average removal performance of the air stripper exceeded the removal performance goal of 90% of all VOCs during continuous mode operation.

Unlike the PVP, the air stripper was easy to operate and required little maintenance and no major repairs. The only problems encountered were iron precipitation inside the air stripper and the need to install a second tray with the stripper to enhance the treatment performance to the desired performance criterion of >90% VOC removal. The PVP, on the other hand, was a complex system that required the permanent presence of a field technician supervising the PVP operation. Frequent control of flow rates, oil levels and other system variables requested the permanent attention of the system operator. Also, the PVP required a constant supply of 270 KW electrical energy that was generated on-site by a diesel electric generator. The generator had to be refilled after approximately every 48 hours of operation, which required a system shut down and special provisions for spill control (berm). Finally, when operating, the PVP system, including the generator, produced a lot of noise and generated a lot of heat. The generator exhaust created another annoyance during operation. All together, the PVP may have demonstrated a VOC treatment capacity that is similar or even better than the air stripper used during this demonstration. Because of that, the PVP may find its application under certain circumstances. However, the additional manpower needed together with the complexity of operating the PVP system made this system more a liability than a treatment alternative.

## 5.6 Technology Comparison

Table 5.14 provides a technology comparison of CDEF to selected alternative DNAPL removal technologies and conventional pump-and-treat. Some of the information given in this table was cited from NFESC, 2001. It is important to note that currently there is no single DNAPL removal technology available that can be used under any site conditions. The selection of an appropriate remediation technology has always been site specific and requires sufficient source zone characterization. The difficulties encountered in this demonstration should serve as an example that even under seemingly “simple” hydrogeologic conditions unexpected problems can be encountered (such as iron precipitation or the presence of a trough at the bottom of the aquifer). The need for site characterization and the difficulty to adequately describe all aspects of a given site have direct impact on the design, cost, and performance of all remediation technologies.

| | **Surfactant/Cosolvent Flooding** | **Cyclodextrin Flushing** | **In-Situ Chemical Oxidation** | **Pump-and-Treat** |
|---|---|---|---|---|
| **Applicability** | Applicable to NAPLs | Applicable to NAPLs | Applicable to NAPLs and dissolved contaminants | Applicable to dissolved contaminants, least effective for NAPLs |
| **Laboratory Design** | Extensive laboratory testing | Some laboratory testing | Some laboratory testing | No laboratory testing |
| **Field Design** | Detailed site characterization required<br>• Locate source zone and delineated its extent<br>• Map hydrostratigraphy<br>• Measure basic aquifer and soil parameters<br>• Characterize the capillary barrier (aquitard) relative to NAPL mobilization design<br>Simulation of well field design and injection/ extraction scheme | Detailed site characterization required<br>• Locate source zone and delineated its extent<br>• Map hydrostratigraphy<br>• Measure basic aquifer and soil parameters<br>• Characterize the capillary barrier (aquitard) relative to NAPL mobilization design<br>Simulation of well field design and injection/ extraction scheme | Detailed site characterization required<br>• Locate source zone and delineated its extent<br>• Map hydrostratigraphy<br>• Measure basic aquifer and soil parameters<br>Simulation of well field design and injection/ extraction scheme | Detailed site characterization required<br>• Locate source zone and delineated its extent<br>• Map hydrostratigraphy<br>• Measure basic aquifer and soil parameters<br>Simulation of well field design and injection/ extraction scheme |
| **Hydrogeologic Constraints** | Sufficiently high aquifer thickness and permeability necessary. Mobility control of NAPL is recommended. | Sufficiently high aquifer thickness and permeability necessary. | Not amenable to mobility control. | Not amenable to mobility control. |

**Table 5.14:** Technology comparison: advantages and disadvantages of selected DNAPL removal technologies (adapted from NFESC.2001)

**Table 5.14:** Technology comparison: advantages and disadvantages of selected DNAPL removal technologies (adapted from NFESC.2001) (Continued)

| | | | | |
|---|---|---|---|---|
| **Effect on Subsurface** | Demonstrated reduction in NAPL saturation to less than 0.05% | Demonstrated reduction of DNAPL saturation by 81% at site with low initial DANPL saturation (Initial $S_N$ = 0.67%). Long-term effects may include enhanced biodegradation facilitate by co-metabolism of CD | NAPL destroyed in-situ in aqueous phase. Potentially destroys (oxidizes) natural organic matter. Risk of sterilizing the treatment zone. Risk of clogging the aquifer. | Large volumes of water need be extracted to remove relatively little contaminant mass. Not amenable for NAPL removal |
| **NAPL Mobilization** | Likely, but can be minimized with proper hydraulic controls and tailoring the surfactant flushing solution | NAPL mobilization is generally not a cause of concern. | NAPL mobilization is generally not a cause of concern. | NAPL mobilization is generally not a cause of concern. |
| **Performance Assessment** | Surfactant residuals in the subsurface may affect performance assessment by PTT. | PTT can be used of performance assessment, although low $S_N$ values can contribute to uncertainty | Limited by dissolution rate of NAPL. Change in NAPL composition can affect performance assessment | PTT can be used of performance assessment |

# 6. Cost Assessment

## 6.1 Cost Reporting

The cost report for the CDEF technology was prepared based on the guidelines provided by the Federal Remediation Technologies Roundtable (FRTR): *Guide to Documenting and Managing Cost and Performance Information for Remediation Projects* (FRTR, 1998). This cost reporting format distinguishes between several cost categories (capital (predominantly fixed), operational and maintenance (predominantly variable), and other technology specific costs and relates the cost of treatment to the mass of media/volume removed and treated. Most system specifications used in the cost reports are identical to thoses employed at NABLC. However, a few modifications have been made based on lessons learned during the CDEF demonstration. These modification, where applicable, are outlined in the following paragraphs.

Table 6.1 summarizes the site conditions at Site 11, NABLC under which the CDEF demonstration was performed. If not noted otherwise, these values were used in the preparation of the cost report.

**Table 6.1:** Summary of the actual demonstration site conditions at Site 11, NABLC.

| Parameter | Value |
|---|---|
| Depth to water table | 2.1-2.4 m bgs (7-8 ft bgs) |
| Depth to aquitard | 7-8 m bgs (21-24 ft bgs) |
| Porosity of aquifer | 31% |
| Hydraulic conductivity of DNAPL treatment zone | $8x10^{-4}$ cm/sec |
| Hydraulic conductivity of aquitard | $3x10^{-8}$ cm/sec |
| Treatment flow rate | 3.4 gpm |
| Number of wells | 8 |
| CD slug size per application | 9 $m^3$ |
| Mass of Soil treated | 49 tons |
| Surface area above treatment zone | 30.3 $m^2$ (326 $ft^2$) |
| Average pre-CDEF VOC conc. [(a)] | 38.3 mg/L |
| Initial DNAPL Saturation ($S_N$) [(b)] | 0.67% |
| 90% DNAPL removal criterion[(c)] | 34.2 liter or 48 kg DNAPL |

(a) Sum of TCE, 1,1,1-TCA, and 1,1-DCE as determined during PTTs
(b) Pre-PTT weighted best estimate
(c) 38 liter DNAPL was initially present at demonstration site (see Table 5.12 and discussion in Section 5.4). Thus, 90% of 38 liters are 34.2 liters.

The effluent treatment cost estimates reflect sites without on-site effluent treatment facilities. Under these circumstances, as was the case at NABLC, cost for an effluent treatment system (such as air stripping) becomes part of the overall technology cost. It was assumed that any off-site effluent discharge from a treatment system must meet all applicable effluent discharge standards.

After 6 to 8 months, the cumulative rental expenditures exceed the equipment purchase price in most cases. Hence, it was assumed that all equipment was purchased if the remediation project lasted longer than 6 to 8 months. Only the cost for activated carbon filter system necessary to treat the VOC off-gas was calculated on per-month basis, even if the treatment duration exceeded 6 months. This approach was selected because spent activated carbon had to be replaced by fresh carbon one on a regular basis.

For the ESTCP demonstration, partition tracer tests served as the principal means for DNAPL source zone characterization and performance assessment. The PTT technology is patented to *Duke Engineering* and license fees may apply. The use of this technology was considered optional for developing cost estimates for full-scale CDEF application. Therefore, the cost for conducting a pre- and post-PTT test are not included in any real-world cost assessments.

A DNAPL source zone investigation was considered part of the CDEF remediation. However, it was assumed that the approximate extent of the DNAPL source zone is already known from previous site investigations (as was the case at this demonstration site).

*Actual Demonstration Cost:* Using the FRTR methodology, the actual cost of the CDEF demonstration was approximately $863,000 (incl. PTTs). A detailed cost report is provided in Appendix VI. Based on the mass of VOC contaminants removed and treated during the flushing with CD (25.8 lbs[1]), the VOC treatment cost was approximately $33,000 per-lb. When relating the treatment cost to the volume of groundwater extracted and treated, the cost was $1.03 per gal. In terms of soil mass treated, the cost was approximately $17,500 per-ton of soil.

*Cost of Real-World Implementation*: This CDEF technology demonstration varied from a real-world implementation in several ways. For example, considerable effort was spent collecting and analyzing samples for technology performance demonstration purposes. Also, in preparation for this demonstration a series of laboratory test were conducted that provided information directly applicable to most, if not all, future CDEF sites. For example, extensive investigations have been conducted to test different sources and quality grades of CD. Future users of the CDEF technology would not need to repeat these tests. In addition, local rules and regulations required the continuous presence of personnel at the site during operation and the implementation of the body-system. The requirement for continuous personnel was in place to ensure that no system failures would occur without personnel present to promptly respond. At a typical real-world CDEF implementation, a computerized SCADA system would be installed to fully automate the pumping operations. In case of system failures a designated responder is paged, which alleviates the need for manning the operation full-time. Also, two treatment approaches were tested (I/E and CPPT) and two VOC treatment alternatives (air stripping and pervaporation) were evaluated as part of this demonstration. On most real-world sites only one treatment approach and method is implemented. Finally, in addition, universities (students and their supervisors) performed most of the work at salaries that differ from commercial contractors. All these activities affected the cost of this demonstration.

[1] The overall VOC mass recovered during the entire demonstration (incl. PTTs) was about 78 lbs.

For this real-world cost assessment, all one-time, demonstration-related costs were removed (such as experimentation, process optimization, non-routing analysis and testing, and excessive sampling and analysis used to evaluate and refine the demonstration). It was assumed that one VOC and two CD analysis were carried out on a daily basis (see Table 6.2) over a period of two months. It was further assumed that no pervaporation equipment was used and that no partition tracer tests were conducted. Also, a SCADA system was implemented, decreasing the number of field personal hours. All remaining costs reflect the actual spending during the ESTCP demonstration. Under these conditions, the real-world CDEF implementation cost is $392,000. A detailed cost report is provided in Appendix VII. Based on the 25.8 lbs VOC removed and treated, the VOC treatment cost was approximately $15,200 per-lb. When relating the treatment cost to the volume of groundwater extracted and treated, the cost is $0.47 per gal. In terms of soil mass treated, the cost is approximately $7,900 per-ton of soil.

*Hypothetical Full-Scale System*: Another significant difference between this ESTCP technology demonstration and a real-world implementation of CDEF technology was the comparable small size of the treatment zone and the scale at which the demonstration was performed (see Tab. 6.1). For example, the mass of soil treated during this demonstration was about 50 tons. Many contaminated sites, however, require treatment of several hundred tons of soil or more. Also, the UF system for CD reconcentration used in the demonstration was not operated continuously (i.e. the UF treatment rates were smaller than the flushing solution extraction rates). The treatment capacity of a full-scale UF system requires treatment capacities that at least equal the volume of extracted flushing solution.

To account for these size and scale issues, a cost report was prepared for a hypothetical full-scale system. It was assumed that a site approximately 11 times larger (600 tons contaminated soil, or 109 $m^3$ flushing volume) than the demonstration site was remediated using CDEF technology. The remediation area was 234 $m^2$ (2,500 $ft^2$). The global degree of contamination (initial DNAPL saturation = 0.67%) and the site conditions (see Table 6.1) were assumed to be the same as during the ESTCP demonstration. The remediation goal was 90% DNAPL mass removal, i.e. 1,415 lbs VOC. It was assumed that a limited DNAPL source zone investigation was needed prior to the CDEF implementation. Table 6.2 summarizes the remediation system performance parameters that were used to calculate remediation cost and duration.

The full-scale site conditions were carefully chosen to closely reflect the conditions that were encountered at *Site 88*, Marine Corp Base Camp Lejeune, North Carolina. At this site, an ESTCP sponsored technology demonstration of surfactant enhanced flushing (SEAR) was recently conducted and detailed costs and performance data are available (NFESC, 2001). The advantage of basing the full-scale CDEF cost assessment on Camp Lejeune site conditions permits cost and performance comparisons of different DNAPL treatment approaches under very similar boundary conditions.

**Table 6.2:** Criteria used to develop remediation cost, CD recovery cost, and full-scale remediation time estimates.

| Criterion | Value |
|---|---|
| Type of CD | Hydroxyl-ß-cyclodextrin; technical grade; unstabilized 40% aqueous solution with pH near neutral |
| Treatment Area | 30 $m^2$ (300 $ft^2$) Small site<br>234 $m^2$ (2,500 $ft^2$) Large site |
| Contaminant Removal Process [(a)] | Air stripping |
| Efficiency of Contaminant Removal Process | > 90% |
| CD recovery from subsurface treatment zone | CPPT: 97%<br>I/E: 79% |
| Average injection well CD concentration | 20% |
| Assumed efficiency decrease of CDEF due to decrease in global $S_N$ over remediation period [(b)] | 25% |
| Efficiency of CD recovery from subsurface | Batch operation: 97%<br>Continuous operation: 79% |
| Efficiency of CD recovery by UF (batch mode) | Batch operation: 90%<br>Continuous operation: 68% |
| CDEF Operation time | I/E: Continuous<br>CPPT: 3 - 6 flushes per week |
| CD mass used | Determined by model |
| CD cost | $2.00 / lbs ($4.50 / kg) |
| Tank requirements [(c)] | 2 x 6,500 gal tank (demo scale)<br>2 x 21,000 gal tank (full-scale) |
| Analytical requirements [(d)] | Continuous operation: 1 VOC and 2 CD analyses per day<br>Batch operation: 1 VOC and 2 CD analyses per flush |
| Labor requirements [(e)] | Continuous operation: 6 man-hrs per day<br>Batch operation: 8 man-hrs per day |

(a) performance evaluation of PVP not considered because of insufficient data.
(b) CDEF efficiency decrease was observed during multi-well CPPTs at the end of the CDEF demonstration. Efficiency decrease was most likely caused by decreasing NAPL saturation in the flushing zone. Value is a conservative estimate.
(c) one tank required for 40% CD stock solution storage, second tank required for storage of recovered CD flushing solution.
(d) one VOC analysis of the extracted and injected solution per day to monitor remediation progress and efficiency. One CD analysis of the extract to confirm effectiveness of the flushing solution. A second CD analysis after UF system to confirm flushing solution target concentration of 20% before reinjeciton. Additional sampling of the effluent may be required, depending on the characteristics of the discharge (i.e. presence of inorganics).
(e) labor requirements during I/E operation include daily system check and maintenance and effluent sampling. Assumes that SCADA system is used for system monitoring during remaining times. Additional work requirements during batch operation include switching treatment system from injection to extraction mode and back. Local rules may require 24/7 site staffing and/or implementation of the body-system (as was the case during this demonstration).

The full-scale cost report was based upon air stripping as the sole VOC treatment technology. An alternative (pervaporation) was not considered because of insufficient cost and performance data. The cost of a full-scale UF treatment system was estimated based on manufacturer's information. However, actual cost of the UF system may deviate by as much as 25% depending on treatment capacity, rental duration, and availability. Also, it was assumed that the membrane filter inside the UF must be replaced twice a year[2].

[2] There was no need to replace the membrane filter during the demonstration. Replacement interval is therefore a best estimate.

Two different treatment approaches were evaluated: (1) line-drive (I/E) and (2) multi-well push-pull (CPPT) treatment. The line drive treatment was assumed to run continuously. It was assumed that six CPPTs were run per week when running the UF in continuous mode. In case the CPPT/UF system was operated in batch mode, two flushes were realized per week. The remaining time was necessary to reconcentrate the recovered CD flushing solution. It was assumed that the UF system for CD reconcentration performed as determined during this demonstration (Tab. 6.2). This conservative estimate leaves ample room for (cost) improvements, because the UF used in the demonstration was a comparable low efficient proto-type. Finally, a cost assessment was provided in case no UF system is used. Table 6.3 summarizes the various scenarios assessed and provides a comparison of the number of wells needed for treating at full-scale.

**Table 6.3:** Comparison of well requirements for full-scale CDEF application (2,500 ft$^2$) at a hypothetical site similar to NAB Little Creek, VA.

| Application | UF Operation Mode | Number of Injection/ Extraction Wells | Number of Injection Wells | Number of Extraction Wells | Number of Hydraulic Control Wells |
|---|---|---|---|---|---|
| I/E | Continuous | - | 14 | 24 | 8 |
| I/E | --- | | | | |
| CPPT | Continuous | 40[(1)] | - | - | -[(2)] |
| CPPT | Batch | 40[(1)] | - | - | -[(2)] |
| CPPT | --- | 40[(1)] | - | - | -[(2)] |

[(1)] Injection/Extraction wells used for push-pull treatment are identical in construction compared to injection, extraction, or hydraulic control wells used during I/E.

[(2)] No hydraulic control wells necessary if groundwater flow velocities are 0.5 cm or less.

An EXCEL model was developed to estimate remediation duration and how much CD mass is needed for achieving the 90% DNAPL mass removal criterion. The model requires as input most of the data summarized in Table 6.1 through 6.3. It was first fitted to the initial DNAPL mass present at the ESTCP demonstration site. After good agreement was reached between DNAPL mass and remediation performance (as determined during this demonstration), the flushing volume was increased from 9 m$^3$ to 109 m$^3$ (or, in terms of soil mass, from 49 tons to 600 tons). The model simulations are shown in the Appendix VIII.

**Table 6.4:** Comparison of full-scale CDEF flushing durations at a hypothetical site under similar conditions to NAB Little Creek, VA.

| Application | UF Operation Mode | CD Flushing Duration (PV/Total months) | |
|---|---|---|---|
| | | Small Site[(1)] 300 ft$^2$ | Large Site[(2)] 2,500 ft$^2$ |
| I/E | Continuous | 2 | 19 |
| I/E | None | --- | 19 |
| CPPT | Continuous | 2 | 2 |
| CPPT | Batch | 4 | 6 |
| CPPT | None | --- | 2 |

[(1)] Contaminated soil mass = 49 tons, pore volume = 9 m$^3$

[(2)] Contaminated soil mass = 600 tons, pore volume = 109 m$^3$

The relatively short duration of the ESTCP demonstration added some additional uncertainty to the cost report. For example, towards the end of the CDEF demonstration the VOC removal efficiency decreased as the result of decreasing NAPL saturation. The rate of CDEF efficiency decrease could not be quantified. Because of this shortcoming, it was assumed that the efficiency decreased by 25% over the remediation period. Based on this assumption, the total number of flushing cycles necessary to reach the remediation end-point criterion (90% mass reduction criterion) was multiplied by an uncertainty factor of 1.25 (see model simulations in Appendix VIII). The full-scale CDEF flushing durations for each treatment scenario are summarized in Table 6.4.

The total life-cycle costs for the three full-scale CDEF treatment scenarios with an UF in operation are summarized in Table 6.5. The life-cycle costs are reported as net present value (NPV). Overhead costs or contingency fees were not included. Associated unit treatment costs for each scenario are also included (on VOC mass and soil mass basis). Detailed cost reports for each scenario (including those two in which no UF was used) are summarized in Appendix IX. A second full-scale cost assessment was developed for a smaller site (see Table 6.2). Refer to Appendix X for details. Table 6.6 shows the implementation cost at the smaller site.

**Table 6.5:** Cost of full-scale CDEF implementation (Treatment area: 234 $m^2$ or 2,500 $ft^2$)

| Cost Category | Sub Category | Cost Scenario | | |
|---|---|---|---|---|
| | | **I/E Approach With UF (continuous mode)** | **CPPT Approach With UF (continuous mode)** | **CPPT Approach With UF (batch mode)** |
| | **FIXED COSTS** | | | |
| Capital Cost | Mobilization/Demobilization | $17,928 | $17,928 | $17,928 |
| | Planning/Preparation/ Engineering | $52,020 | $52,020 | $52,020 |
| | Site Investigation | $101,850 | $101,850 | $101,850 |
| | Site Work | $18,600 | $18,600 | $18,600 |
| | Equipment – Structures | $ - | $ - | $ - |
| | Equipment–Process Equipment | $288,039 | $60,974 | $60,974 |
| | Start-up and Testing | $16,880 | $16,880 | $16,880 |
| | Other–Non Process Equipment | $11,300 | $8,050 | $11,300 |
| | Other - Installation | $119,303 | $117,854 | $117,854 |
| | **Sub-Total**: | **$626,130** | **$394,156** | **$397,406** |
| | **VARIABLE COSTS** | | | |
| Operation and Maintenance | Labor | $150,377 | $23,026 | $58,277 |
| | Materials / Consumables | $3,251,620 | $1,796,000 | $838,880 |
| | Utilities / Fuel | $52,921 | $5,808 | $9,401 |
| | Equipment Cost (rental) | $161,301 | $86,025 | $236,779 |
| | Chemical Analysis | $70,925 | $7,380 | $35,160 |
| | Other | $28,522 | $8,358 | $18,070 |
| | **Sub-Total**: | **$3,715,666** | **$1,926,597** | **$1,196,567** |
| Other Technology Specific Cost | Disposal, well cuttings | $16,500 | $16,500 | $16,500 |
| | Disposal, liquid waste | $5,100 | $500 | $1,500 |
| | Site Restoration | $1,080 | $1,080 | $1,080 |
| | **Sub-Total**: | **$22,680** | **$18,080** | **$19,080** |
| | **TOTAL** | **$4,364,475** | **$2,338,833** | **$1,613,053** |
| | **Quantity Treated – Soil (tons)** | **600** | **600** | **600** |
| | **Unit Cost (per lbs VOC removed and treated)** | **$7,274** | **$3,898** | **$2,688** |
| | **Quantity Treated – VOC mass (lbs)** | **1,415** | **1,415** | **1,415** |
| | **Unit Cost (per lbs VOC removed and treated)** | **$3,085** | **$1,653** | **$1,140** |

| **Table 6.6:** Cost of full-scale CDEF implementation (Treatment area: 30 m$^2$ or 300 ft$^2$) | | | | |
|---|---|---|---|---|
| | | **Cost Scenario** | | |
| **Cost Category** | **Sub Category** | **I/E Approach With UF (continuous mode)** | **CPPT Approach With UF (continuous mode)** | **CPPT Approach With UF (batch mode)** |
| **FIXED COSTS** | | | | |
| Capital Cost | Mobilization/Demobilization | $17,928 | $17,928 | $17,928 |
| | Planning/Preparation/Engineering | $38,020 | $38,020 | $38,020 |
| | Site Investigat ion | $17,065 | $17,065 | $17,065 |
| | Site Work | $6,400 | $6,400 | $6,400 |
| | Equipment – Structures | $ - | $ - | $ - |
| | Equipment – Process Equipment | $14,456 | $14,456 | $14,456 |
| | Start-up and Testing | $8,640 | $8,640 | $8,640 |
| | Other–Non Process Equipment | $8,050 | $8,050 | $8,050 |
| | Other - Installation | $36,784 | $32,229 | $32,229 |
| | **Sub-Total**: | **$147,343** | **$147,343** | **$142,787** |
| **VARIABLE COSTS** | | | | |
| Operation and Maintenance | Labor | $23,026 | $19,429 | $50,371 |
| | Materials / Consumables | $469,400 | $151,280 | $73,320 |
| | Utilities / Fuel | $4,818 | $4,756 | $9,513 |
| | Equipment Cost (rental) | $55,273 | $55,267 | $110,547 |
| | Chemical Analysis | $7,380 | $7,380 | $6,480 |
| | Other | $8,716 | $8,358 | $8,716 |
| | **Sub-Total**: | **$568,613** | **$248,470** | **$258,947** |
| Other Technology Specific Cost | Disposal, well cuttings | $3,900 | $3,900 | $3,900 |
| | Disposal, liquid waste | $500 | $500 | $1,000 |
| | Site Restoration | $1,080 | $1,080 | $1,080 |
| | **Sub-Total**: | **$5,480** | **$5,480** | **$5,980** |
| | **TOTAL** | **$721,436** | **$397,801** | **$407,714** |
| | **Quantity Treated – Soil (tons)** | **49** | **49** | **49** |
| | **Unit Cost (per lbs VOC removed and treated)** | **$14,723** | **$8,118** | **$8,321** |
| | **Quantity Treated – VOC mass (lbs)** | **105** | **105** | **105** |
| | **Unit Cost (per lbs VOC removed and treated)** | **$6,871** | **$3,789** | **$3,883** |

## 6.2 Cost Analysis

Compared to the actual demonstration cost, the real-world CDEF implementation cost is are about 55% less expensive. The difference in cost is attributed to one-time, demonstration-related costs, such as experimentation, process optimization, non-routing analysis and testing, and excessive sampling and analysis used to evaluate and refine the demonstration.

The full-scale cost analysis reveals that scale and treatment approach determine the treatment cost. At small and large scale, respectively, the implementation of the multi-well push-pull approach was approximately 53% to 64% less expensive than the line-drive CDEF. The main cost driver for the line-drive CDEF was the material cost (i.e., amount of CD mass needed to achieve the remediation goal). The line-drive material cost accounted for 65% (small site) and 75% (large site) of the total life-cycle costs. Compared the push-pull approach, significantly more CD was needed because of the comparable low CD recovery efficiencies during line-drive flushing. Another cost driver was the comparable long remediation time necessary when implementing the line-drive approach at large scale sites (19 months, see Table 6.4). Longer remediation times resulted in much higher labor and equipment rental and purchase cost compared to the shorter multi-well push-pull treatment scenarios.

The lowest costs overall were realized by implementing multi-well push-pull CDEF and running the UF in batch mode. Under these conditions, 185 tons of CD were applied at the large site (accounting for 52% of the total life-cycle costs). If the UF were run in continuous mode, the amount of CD needed increased to 407 tons (accounting for 78% of the total life-cycle cost). Although running the UF continuously resulted in shorter remediation durations, the additional CD costs exceeded the cost savings realized because of lower labor and equipment rental costs.

Very similar life-cycle costs were generated when operating the UF in batch or continuous mode at the small scale (Table 6.6). The main reason for this similarity was that the remediation duration decreased from 6 to 4 months when using the batch mode approach at the smaller scale (see Table 6.4). Under the same conditions, the duration of the continuous treatment approach remained essentially unchanged because of hydraulic flow constriction and UF treatment capacity issues. In terms of unit treatment costs, the small scale unit treatment cost was more than twice as high as at the large site. This is mainly due to the fact that much more effort (site investigation, mobilization/ demobilization etc.) has to be expended to implement CDEF at small sites.

### 6.3 Cost Comparison

In this section, the cost of CDEF treatment for DNAPL removal is compared to the cost of a conventional remediation technology (pump-and-treat (P&T) DNAPL source zone containment) and two innovative in-situ treatment methods (surfactant enhanced flushing, SEAR, and six-phase resistive heating). The cost comparison was developed for the large site scenario at NAB Little Creek (section 6.1 and 6.2). As Table 5.7 shows, the site and operating conditions were very similar to the conditions encountered at the at the 2,500 ft$^2$ *Site 88* at the Marine Corp Base Camp Lejeune, NC (see NFESC 2001). Both sites were contaminated by similar volumes and types of DNAPL and can be remediated within a few months. The site area, hydrogeologic conditions, including treatment volume and aquifer thickness treated, and treatment approach (enhanced flushing) were very similar. Two main differences are noted. First, a lower initial DNAPL saturation at NAB LC (0.67% versus 2% at MCB CL) may affect (= underestimate) the performance of CDEF technology relative to SEAR. Second, the remediation end-point criterion was defined differently.

In addition to the site and operation similarities, the SEAR costs estimate was developed based on the same ESTCP approved cost assessment strategies used for this CDEF cost report. For example, the cost of pre- and post-treatment site characterization of the DNAPL source zone were not included in the either the SEAR (incl. resistive heating) or the CDEF cost assessments. Also, it was assumed that the technology vendors will be presented with a well-characterized site (as was the case for the CDEF cost assessment). Because of these similarities, we feel highly confident in using the SEAR costs reported by NFESC (including those for the resistive heating alternative) and compare them with our CDEF cost estimates.

**Table 6.7:** Comparison of site conditions at NAB Little Creek, VA, and MCB Camp Lejeune, NC (site information compiled from NFESC, 2001).

| Parameter | CDEF Full-Scale | Camp Lejeune |
|---|---|---|
| Report date | 2003 | 2001 |
| Surface area | 2,500 $ft^2$ | 2,500 $ft^2$ |
| Depth to water table | 2.1-2.4 m bgs (7-8 ft bgs) | 2.1-2.7 m bgs (7-9 ft bgs) |
| Depth to aquitard | 7-8 m bgs (21-24 ft bgs) | 6-7.7 m bgs (18-20 ft bgs) |
| Porosity of aquifer | 31% | 30% |
| Hydraulic conductivity of DNAPL treatment zone | $8x10^{-4}$ cm/sec | $1x10^{-4}$ cm/sec (low k) |
| Hydraulic conductivity of aquitard | $3x10^{-8}$ cm/sec | $2x10^{-7}$ cm/sec |
| Number of wells | 46 Line-drive(1)<br>40 Push-Pull | 46 Line-drive (1) |
| Type of treatment | Enhanced flushing | Enhanced flushing |
| Flushing agent | Cyclodextrin (20 wt%) | Surfactant (4 wt%)<br>Cosolvent (8 wt%) |
| Treatment flow rate | 6 gpm | 6 gpm |
| Duration of Operation | 19 months (I/E)<br>2 – 6 months (CPPT) | 4.25 months (127 days) |
| Tankage requirements | 2 x 21,000 gal steel tanks | 2 x 21,000 gal steel tanks |
| Primary contaminant | TCE and 1,1,1-Tri | PCE |
| Contaminant removal process | Air stripping | Air stripping |
| Average initial DNAPL saturation ($S_N$) (2) | 0.67% | 2% |
| Initial DNAPL volume (2) | 413.5 liter | 397 liter(3) |
| End-point criterion | 90% reduction of DNAPL | Natural attenuation becomes possible |

(1) 24 injection wells, 14 extraction wells, 8 hydraulic control wells
(2) Initial DNAPL saturation ($S_N$) is PTT based
(3) see NFESC 2001, pg. 72.

**Table 6.8:** Summary of CDEF and alternative technology cost for full-scale application for remediation of a DNAPL source zone similar to NAB Little Creek, VA. All cost rounded to nearest thousand.

| Cost Category | **CDEF** Line-drive UF operating continuously | **CDEF** Push-Pull UF operating in batch mode | **SEAR**(1) | **P&T**(1)(3) | **Resistive Heating**(1) |
|---|---|---|---|---|---|
| Capital Investment (2) | $524,000 | $296,000 | $890,000 | $120,000 | $347,000 |
| Contaminant Disposal Cost | $5,000 | $2,000 | $4,000 | $30,000 | $94,000 |
| O&M Cost | $3,716,000 | $1,197,000 | $498,00 | $1,385,000 | $198,000 |
| **Total Present Day Cost** | **$4,245,000** | **$1,495,000** | **$1,392,000** | **$1,535,000** | **$639,000** |

(1) Costs were developed for MCB Camp Lejeune (NFESC, 2001). Very similar site conditions and the implementation of similar cost assessment strategies permit comparison of these cost estimates with (hypothetical) full-scale CDEF implementation at NAB Little Creek.
(2) Cost of characterizing DNAPL source zone before and after treatment not included. Also, post-treatment monitoring of site may be required. Cost not included.
(3) Undiscounted present day value of reoccurring and periodic O&M cost in today's dollars spread over 30 years of operation. This total includes $45,000 of recurring annual operating and maintenance cost incurred over every year of operation, $13,000 in periodic maintenance incurred every 10 years, and $13,000 in periodic maintenance incurred every 20 years (after NFESC, 2001).

Table 6.8 provides a cost comparison of CDEF, SEAR, resistive heating, and P&T. The cost category format was adapted from NFESC, 2001. All innovative remediation alternatives were assumed to last a few months only. The exception is the CDEF line-drive approach, which lasted 19 months. Conventional P&T cost incurred over a 30-year period. All costs were based on present value (NFESC, 2001). The treatment alternative "multi-well push-pull with UF operating in continuous mode" was not included in Table

6.8 because unless a more effective UF system becomes available, this approach cannot compete with the multi-well push-pull approach and running the UF in batch mode.

Based on the cost comparison provided in Table 6.8, CDEF in push-pull mode can compete with SEAR. Both innovative remediation technologies are only little less expensive (on present day value basis) compared to conventional P&T. However, in contrast to P&T, much shorter remediation times are realized. This not only reduces the hazardous waste exposure time, but it also results in returning a site to the real-estate market much earlier (or permit earlier re-use). CDEF in line-drive operation was the most expensive innovative remediation technology, resistive heating was the cheapest.

Simply looking at the bottom line may be attractive in many cases, but each technology inherits distinct advantages that set it apart from the rest. For example, cyclodextrin is non-toxic and eventually degrades in the subsurface. These are important acceptance criteria for state and federal regulators, which may favor the implementation of CDEF in some cases. Which remediation technology to use is very site specific and depends on local customs and regulations. Finally, future advances in treatment technology, for example, availability of a more effective UF filter material, may decrease the implementation cost.

# Section 7. Regulatory and Technology Implementation Issues

## 7.1 Environmental Regulations

This pilot test was performed under the CERCLA (42 USC 9601 et seq.) statutory framework. As such, compliance with federal, state, and local statutes was maintained as Applicable or Relevant and Appropriate Requirements (ARARs). ARARs for this site included, but were not limited to the Resource Conservation and Recovery Act (RCRA, 42 USC 6901 et seq.), the Federal Facilities Compliance Act (FFCA, 42 USC 6901 Note, 6908), the Clean Air Act (CAA, 42 USC 7401-7671q.), Executive Order 12088 (Federal Compliance with Pollution Control Standards), Executive Order 12580 (Superfund Implementation), the Clean Water Act (CWA, 33 USC 1251-1387), the Safe Drinking Water Act (SDWA, 42 USC 300f et seq.), and the Virginia Water Quality Standards (9 VAC 25-260-5 et seq.). These regulations drove the performance criteria listed in Table 4.1. Under these provisions, maximum contaminant levels (MCL, SDWA) for dissolved VOC compounds (and other) are established. The MCL would be the remediation goal for groundwater clean up at Site 11 and would need to be reached before regulatory closeout of the site could be achieved. The CAA regulated discharge from the air stripper. The CWA and Virginia Water Quality Standards regulated discharge requirements for water treated below the MCL.

## 7.2 Approach to Regulatory Compliance and Acceptance

Since identifying NAB Site 11 as a potential test site, close working relations were established with representatives of the Navy, appropriate regulatory agencies involved, and local community members. Prior to the ESTCP demonstration, a Partnering Meeting was held to present the concept of the study. The meeting was attended by VADEQ, Navy, USEPA, CH2MHill and all PI's of this project. During this meeting, the technology was presented and it was discussed what was required to implement the technology demonstration at Site 11 during summer 2002. This first meeting was followed by conference calls and frequent information exchanges to obtain the necessary concurrence and to prepare the field test.

Upon arrival at the field site in early June, a kick-off meeting was held at NABLC. This meeting set the rules that had to be followed during the demonstration, e.g. defined the chain-of-command and security requirements while working on the Little Creek base and laid out an emergency response plan.

During the entire ESTCP demonstration, any issues requiring regulator input, such as obtaining permission for discharging treated effluent to the storm drain, were closely coordinated with the appropriate personnel/agencies. In addition, the community was informed of the CDEF activities at Site 11 via the NABLC Restoration Advisory Board (RAB). The board consisted of members from the public, regulators and members of the military environmental restoration community. The RAB toured the demonstration site and inspected the ongoing site activities.

The exchange of information and results obtained during the demonstration continued after the demonstration. A formal, comprehensive presentation of the demonstration results is planned for the near future, i.e. after publication of this final report and after an extensive follow-up site investigation at Site 11 is completed later this summer.

### 7.3 End-User Issues

In a report of the Institute for Defense Analyses (O'Brien, 2001), the primary goal in most industrial remediation projects is to achieve an environmentally acceptable, expedited cleanup of a site at a fixed price. Other related objectives include:

- Limiting exposure to risks associated with environmental cleanup
- Predictable budgeting and cash flow management
- Obtaining financial assurance and insurance to secure contractor performance to adequately protect its, and the buyer's, interests
- Improving productivity by redirecting resources to core business activities
- Accelerating the transfer of distressed real estate assets
- Maintaining adequate level of management control
- Obtaining enhanced tax position

The demonstration addressed these issues by demonstrating that environmentally acceptable, expedited cleanup of a DNAPL site at predictable cost and risk is possible (see separate *Cost and Performance Report*). Although this demonstration has encountered several unanticipated problems (e.g. lower than anticipated treatment rates etc.), none of them posed an obstacle for the CDEF technology. In fact, it was demonstrated that CDEF technology can easily be adapted to changing field conditions, if necessary. One major shortcoming of this demonstration was, however, that not all of the predefined objectives were met (for example, the DNAPL mass removal realized during the demonstration was short of the expectations). The main reasons, as outlined in the preceding chapters, were time constraints and lower than anticipated initial DNAPL saturation in the source zone. A longer treatment duration together with higher initial contaminant concentrations would have undoubtedly increased the CDEF effectiveness. Where necessary, we tried to compensate for these shortcomings by extrapolating the measured CDEF effectiveness data using conservative estimates.

*Procurement issues*: Although this was the first time a membrane filter was used for cyclodextrin recovery, the underlying technology is commercially-off-the-shelf (COTS). All other major pieces of equipment (e.g. air stripper, PVP, sandfilters, pumps, etc.) are also COTS. With a few exceptions (e.g. air stripper), none of the major pieces of equipment was purchased for this demonstration. Equipment purchase may be more economical if more than just one site is being remediated by CDEF technology or if a particular site requires longer than 6 to 8 months remediation time.

As with most remediation projects, the CDEF technology demonstration had to be customized for application at this particular site. Customization issues included (1) design of the well field and sampling protocols, (2) scaling of the treatment units to site specifications (i.e., type and concentration of target contaminants), and (3) other site specific conditions, such as local regulations and customs. Currently, it appears that no patents or other proprietary claims complicated the application of CDEF technology.

This demonstration has already received national and international attention. For example, the cyclodextrin technology was featured in *Business Week* and the *Civil Engineering Magazine* as well as in radio interviews and internet news magazines. Beyond that, presentations of the CDEF technology have been given for clients in the environmental remediation industry as well as to the scientific community. Including several papers that have appeared in scientific journals, the CDEF technology was presented at over 20 occasions. A preliminary website dedicated to CDEF technology was set up (http://www.ri-water.geo.uri.edu/cyclodextrin.asp). This website will eventually provide a link to this report and other technical and scientific information that pertains to CDEF technology.

There are already first results of our information dissemination effort visible. For example, *BEM Systems*, Inc. requested our technical assistance in designing a cyclodextrin remediation study at Patrick Air Force Base, Florida. ARCADIS Inc. is considering the implementation of a modified CDEF system at a site in Colorado. Also, *IEG Technologies* INC, and the Europe based *Alsthom Environmental Consulting* have expressed interest in CDEF technology. These relations will be further developed and expanded.

# Section 8. Lessons Learned

Future applications of CDEF will profit from several lessons learned during this ESTCP sponsored field demonstration. The following is a summary of the most important lessons.

Expect the unexpected. This lesson, although trivial sounding, was probably the most important lesson learned. A lot of effort went into preparation of the CDEF demonstration, including extensive site investigations and negotiations with regulators and suppliers of specialized equipment and services. There were several instances when these efforts were wasted. A few of the unexpected obstacles encountered include:

- Withdraw of consent to discharge to POTW
- Damaged equipment
- Treatment zone heterogeneities
- Lower than anticipated DNAPL saturation in the source zone
- High level base security

Most of these problems were defused in the field because of excellent working relations with local and regional decision makers or because of the easiness of adaptating the CDEF system to changing boundary conditions. Those problems that could not be solved in the field, e.g. repair of damaged equipment, required in a few instances modification or scaling back the demonstration objectives.

The lower than anticipated DNAPL saturation in the source zone (ca. 0.67%) caused a big problem, because for demonstration purposes, we were reliant on a site with a higher, more typical $S_N$ value (>1%). Not only would have our technology benefited from higher $S_N$ values (because a disproportionably large fraction of DNAPL mass was removed during water flushing (= PTT)), but we also would have been able to fully utilize the PTT technology. This is because the PTTs were conducted at the lower detection limit of this method and the resulting $S_N$ estimates are not quite as solid as they would have been under higher $S_N$ conditions. Thus, comparison of pre- to post-demonstration DANPL saturations are somewhat problematic. At the same time, the low initial DNAPL saturation skewed the CDEF efficiency, i.e. made it appear less effective compared to the P&T alternative.

Overall, it is quintessential for the success of a demonstration to be able to adapt to unexpected changes, have the necessary contingency plans ready and, even more important, keep open the lines of communications between all parties involved.

CDEF outperformed conventional pump-and-treat. The presence of CD in the flushing solution enhanced the contaminant mass removal up to 19 times. Overall, CDEF removed three times as much VOC per day (CPPT) compared to conventional P&T. Based on partition tracer tests before and after the CDEF demonstration, the DNAPL saturation was decreased by more than 81% during the demonstration.

CPPT approach outperformed I/E approach. This ESTCP sponsored CDEF demonstration was intended as an assessment of the I/E approach. Unanticipated problems running the I/E system in field (e.g. iron precipitation and well clogging) lead to modification of the treatment approach in favor of CPPT. The assessment of both treatment approaches showed that CPPT outperformed the I/E in several ways. For example, CPPT is about 50% cheaper than I/E and, depending on the CPPT scenario, achieves the remediation scenario faster.

Cyclodextrin solution can be reconcentrated but further improvements of the UF process are needed. The demonstrated CD reconcentration efficiencies of the UF system ranged from 68% in continuous mode to 90% in batch mode. Additional technology developments may benefit the economics of CD recovery. For example, if the UF efficiency in continuous mode operation can be enhanced from 68% to 80%, the resulting cost savings are substantial and would justify the use of UF technology.

Conventional air stripping is preferred over PVP. Although the VOC removal efficiency of the PVP system tested during the demonstration was higher compared to a conventional air stripper, the PVP required significantly more operational effort. Besides the problems caused by running a damaged PVP, the logistics necessary to operate the PVP during this demonstration included a dedicated field technician and the presence of a large diesel electric generator to provide the necessary electrical power. Also, the PVP produced a stream of enriched VOC effluent that must be disposed off-site or in an adequate on-site treatment facility. The air-stripper, on the other hand, does not produce any hazardous wastes. The only major maintenance problem encountered running the air stripper was caused by iron precipitation. This commonly encountered problem can be addressed by operating the air stripper under anaerobic conditions. Although the demonstration field data did not support a full-scale cost assessment of the PVP system, the overall cost of operating the air stripper was significantly lower during this demonstration.

PTT may have practical quantification limit. There is growing concern in the scientific community about the performance of the PTT technology at low DNAPL saturations. The PTT technology is probably most useful when $S_N > 0.5\%$. At many sites, the probable remediation end-point criterion is 0.05%, PTT technology may not provide an accurate measure of the cleanup performance at these low NAPL saturation levels. It is suggested to support the PTT results by other mass balancing means, for example by MIP or Geoprobe measurements. Also, using a numerical model is critical for the design of PTTs. Without such a model in place, the tracer breakthrough time during this demonstration would have been underestimated. This could have resulted in a miss of the BTC.

Base security status affects operation. This demonstration was carried out during times of national crises, i.e. shortly after the 9/11 events and war overseas. During the demonstration, base security at NAB Little Creek base was very strict. Any personnel working on base was subjected to extensive background checks that lasted from a few days to two weeks. These security requirements caused significant delays bringing in personnel without prior security clearance, e.g. truck drivers or service technicians. This had direct consequences for the demonstration because fast response, for example, to broken equipment in need of repair, was difficult.

Collaboration with local consultant. The demonstration would have benefited from having a local consultant on the payroll. Limited services were provided by CH2MHill , the Naval Facilities Engineering Command, Commander Navy Mid-Atlantic Region, and NABLC's public works department in many ways, however, it would have been beneficial to have a local consultant at hand for obtaining unforeseen services and conduct negotiations with suppliers. The precious time that would have been freed up for the PI's could have been spent more effectively on advancing the demonstration.

Additional field demonstration at larger site may benefit the economics of CDEF. The demonstration site at NABLC was comparable small. A repeat of the CDEF demonstration at a larger site would provide further inside into the economics of the remediation alternative. Also, the lessons learned during this ESCTP sponsored study could be implemented and would contribute to an even more robust economic data base.

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# Appendix I:
# Demonstration Plan

Acrobat Document

Click on Icon to open Demonstration Plan

<u>Note:</u>
Large File, contains 143 pages

File can also be downloaded via: ftp://geo.uri.edu/TB

# Appendix II: Points of Contacts

| POINT OF CONTACT Name | ORGANIZATION Name Address | Phone/Fax/email | Role in Project |
|---|---|---|---|
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| Roy Wade | Research Environmental Engineer<br>US Army Engineer Waterway Experiment Station<br>Environmental Engineering Division<br>ATTN: CEWES-EE-R<br>3909 Halls Ferry Road<br>Vicksburg, MS 39180-6199 | Phone: 601.634-4019<br>Fax: -4844<br>WADER@wes.army.mil | ESTCP Liaison Officer |
| Matt Louth | CH2MHill<br>Virginia Beach Office<br>5700 Thurston Ave.<br>Suite 120<br>Virginia Beach, VA 23455 | Phone: 757.460 3734-17<br>Fax: 703.796.6193<br>mlouth@ch2m.com | CH2M HILL Activity Manager for Little Creek |
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| Mary Cooke | Remedial Project Manager (3HS13)<br>USEPA Region III<br>Federal Facilities Branch<br>1650 Arch Street<br>Philadelphia, PA 19103-2029 | Phone: 215.814-5129<br>Fax: - 3051<br>cooke.maryt @epamail.epa.gov | USEPA Region III Remedial Project Manager |

| | | | |
|---|---|---|---|
| Bob Schirmer | NAB Little Creek<br>Department of the Navy, Atlantic Division<br>Virginia Beach, VA 23455 | Phone: 757-322-4751<br>FAX: 4805<br>Email:SchirmerRG@efdlant.navfac.navy.mil | LANTDIV Section Head |
| Dawn Hayes | LANTNAVFACENGCOM<br>Code EV22DH<br>1510 Gilbert Street<br>Norfolk, Va 23511-2699 | Phone: 757.322.4792<br>Fax:4805<br>HayesDM@efdlant.navfac.navy.mil | LANTDIV RPM |
| Wilkie Din | Navy Public Works Center<br>Regional Environmental Group<br>Code 970, Suite 211<br>9742 Maryland Avenue<br>Norfolk, VA 23511-3095 | Phone: 757.444.3009 x394<br>Fax: 757.444.3000<br>dinw@pwcnorva.navy.mil | PWC Environmental Engineer |
| Stephanie McManus | Commanding Officer<br>Naval Amphibious Base Little Creek<br>Base Civil Engineering, Environmental<br>1450 Gator Blvd.<br>Attn: Ms. Stephanie McManus)<br>Norfolk, VA 23521-2616 | Phone: (757) 462-2517<br>Fax (757) 462-7060 | NAB Little Creek Environmental Supervisor |
| John Ballinger | | | Community Outreach Coordinator |
| ***NAB Little Creek and other contacts*** | | | |
| Glenn Roundtree | Commanding Officer<br>NAB Little Creek<br>Base Civil Engineering, Environmental<br>1450 Gator Blvd.<br>Virginia Beach, VA 23521-2616 | Phone: 757-462-2517 | NAB Little Creek contact |
| NAB Little Creek Response Operator | NAB Little Creek<br>Virginia Beach, VA 23455 | Phone: x4444 (on base)<br>757-363-4444 (off base) | Security/Fire/ Ambulance |

**Table I:** Points of contact

# Appendix III: Photos of the CDEF Demonstration

Plate 1: Demonstration site with Building 3651 in background.


Plate 2: Overview of well field with storage tanks, air stripper, and central sampling table in background.

Plate 3: Overview of field site. Left side, air stripper and three activated carbon filter units. Upper center, blower for air stripper and PVP unit. Right, generator. Right corner: central sampling table and sand filter sitting inside berm.


Plate 4: Detail of the well field with Building 3651 in background.


Plate 5: View of the tank farm. Two large tanks in foreground had a 6,500 gal capacity. The white tank to the right was a 2,500 gal storage tank.

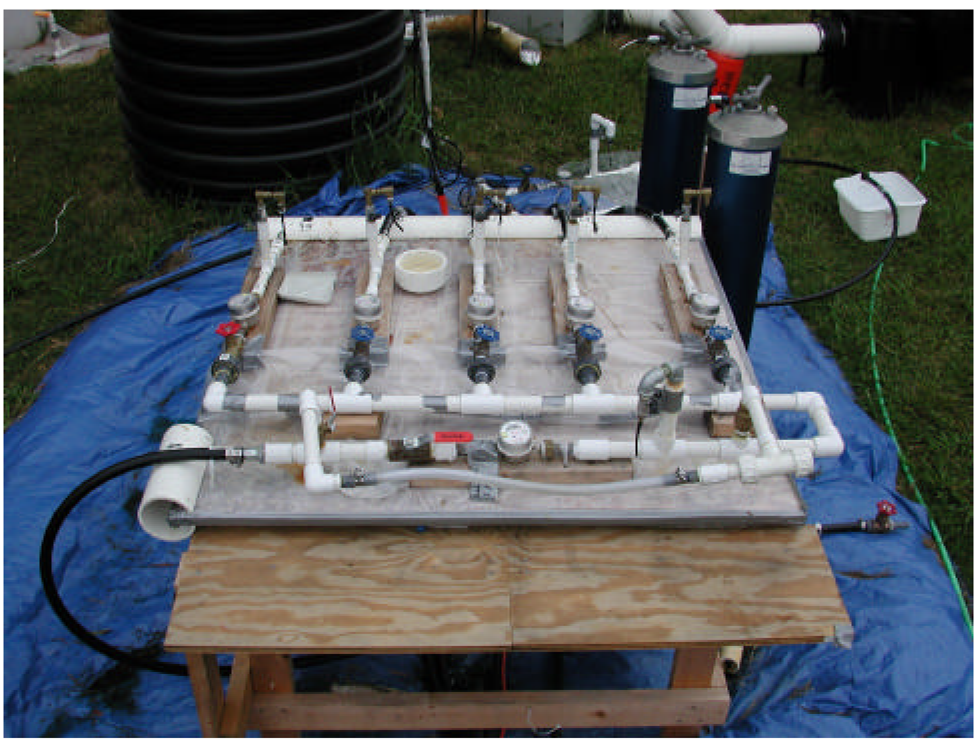

Plate 6: Central sampling table with five flow meters and sample ports. Flow meter in foreground was used to measure total flow.

Plate 7: Extraction well head. Gray box on the left side contained well electronics.

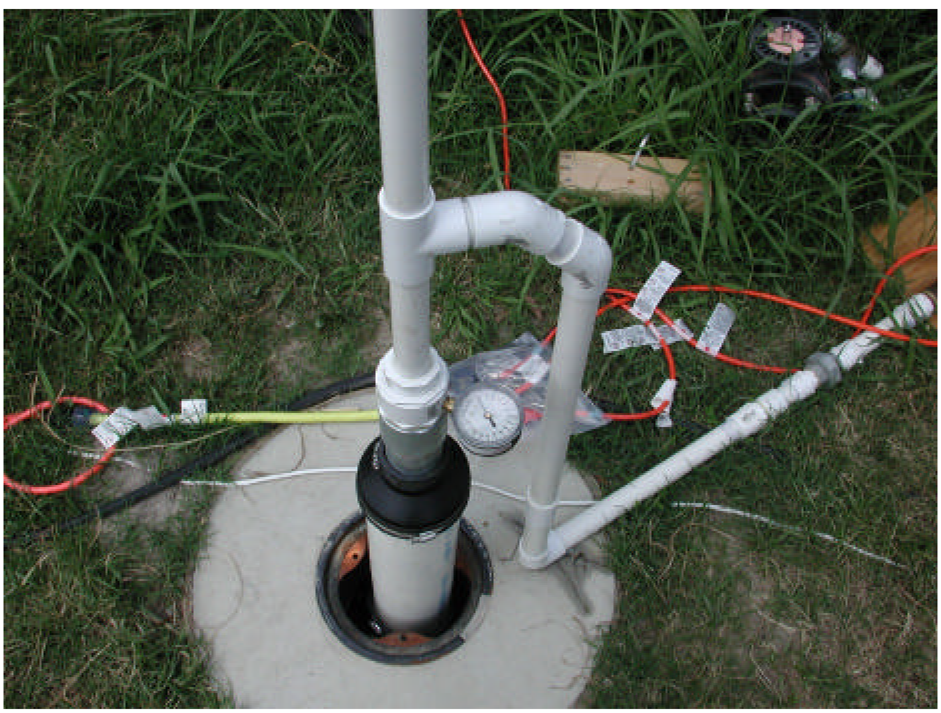

Plate 8: Injection well head with pressure gauge.

Plate 9: Sample port for sampling air stripper effluent

Plate 10: Sand filter for removing suspended solid before entering the treatment system. Background: central sample table.

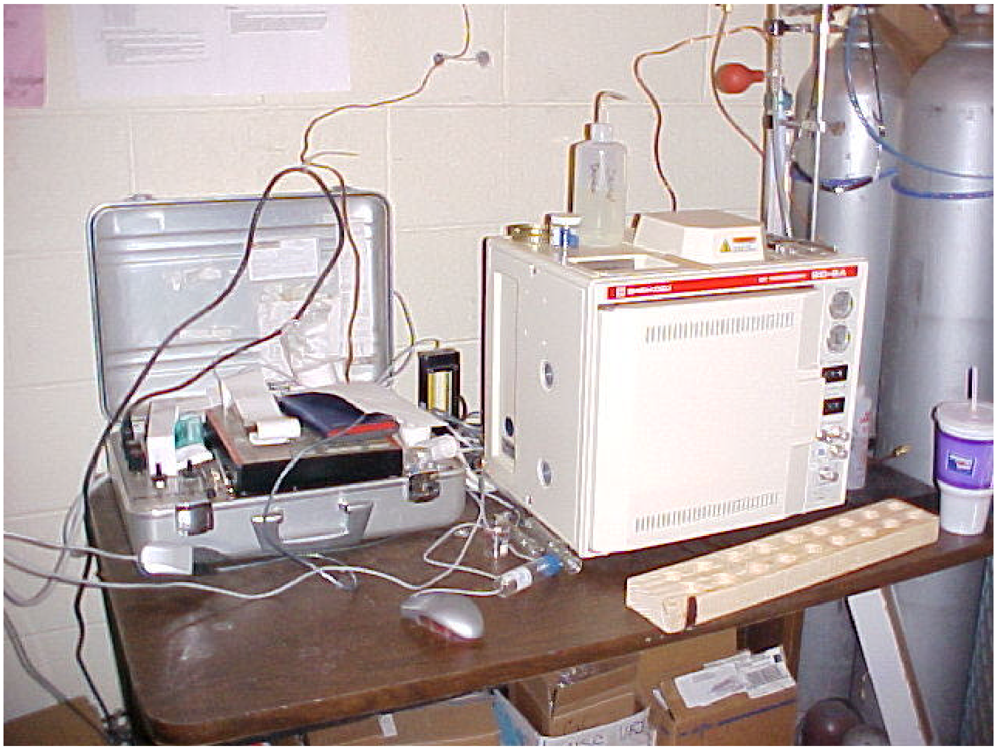

Plate 11: Shimadzu GC-8 gas chromatograph (right) was used in the field for gas tracer measurements. The field GC (left) served initially for on-site TCE measurements.

Plate 12: Shimadzu TOC analyzer used at the field site for cyclodextrin analysis/

Plate 13: Detail of air stripper tower for VOC treatment (purchased from IEG Technology, INC.)

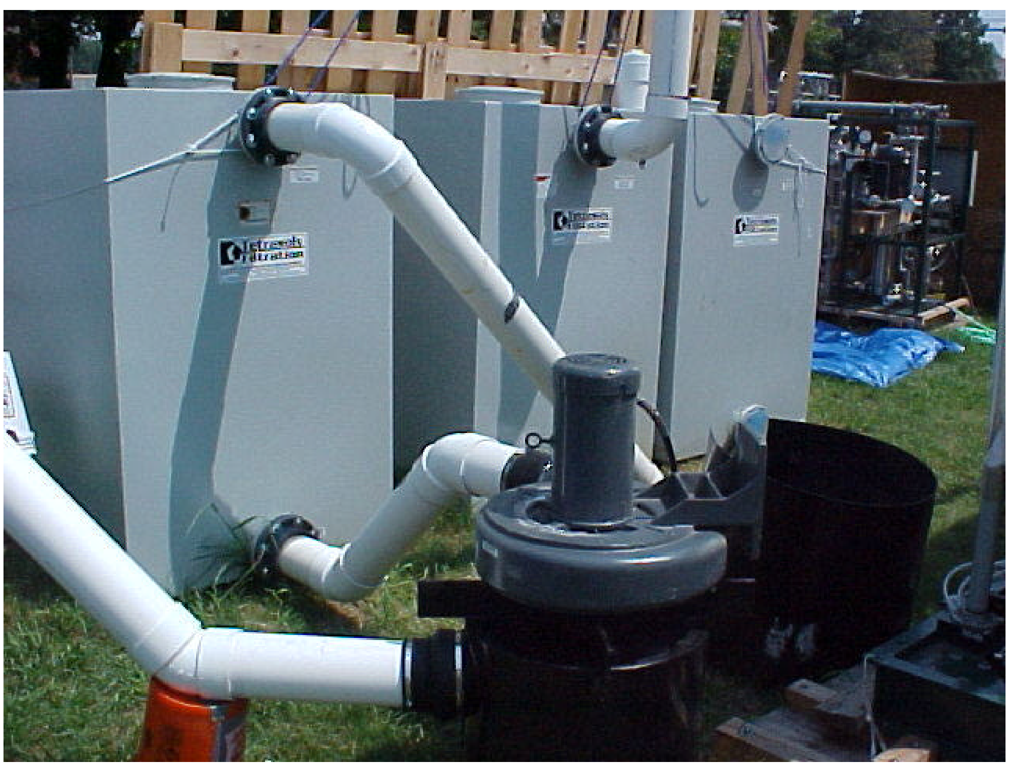
Plate 14:  Detail of the off-gas treatment system with blower in foreground and air-activated carbon filters in background.  Each filter had a dedicated sample port for air-VOC measurements.


Plate 15: 350 KW diesel electric generator. To the right, 250 gal plastic storage tank for PVP effluent. Notice, that generator and tank a surrounded by berms for safety.

Plate 16: Ultrafiltration system for CD reconcentration (rented from MTR INC.). Notice 150 gal internal storage tang that permitted operation in batch mode.

Plate 17: Pervaporation unit used for VOC treatment (rented from MTR, INC).

Plate 18: Chiller unit (part of PVP system). This critical part of the PVP system was damaged during site mobilization (rented from MTR, INC).

# Appendix IV:

## Determination of hydraulic conductivity from Soil Sieve Results

*Sieve Analysis Method*

The hydraulic conductivity of sandy sediments can be estimated from the grain-size distribution curve by the Hazen method (Fetter, 2001). A sieve analysis is used to determine the distribution of sediment in a sample. The grain size distribution of sediment may be conveniently plotted on semi-log paper. The cumulative percent finer by weight is plotted on the arithmetic scale and the grain size is plotted on the logarithmic scale. The grain size of the sand fraction is determined by shaking the sand through a series of sieves with decreasing mesh openings. The uniformity coefficient of sediment is a measure of how well or poorly sorted nature of the soil. The uniformity coefficient, $C_u$, is the ratio of the grain size that is 60% finer by weight, $d_{60}$, to the grain size that is 10 % finer by weight, $d_{10}$. To calculate the uniformity coefficient, the following formula is used: A sample with a $C_u$ less than 4 is well sorted and if it is greater than 6 it is poorly sorted (Fetter, 2001). The Hazen method is applicable to sands where the effective grain size ($d_{10}$) is between approximately 0.1 and 3.0 mm. The Hazen approximation is:

$$K = C(d_{10})^2$$

where K is hydraulic conductivity (cm/s), $d_{10}$ is the effective grain size (cm) and C is a fitting coefficient based on the following table:

| | |
|---|---|
| Very fine sand, poorly sorted | 40-80 |
| Fine sand with appreciable fines | 40-80 |
| Medium sand, well sorted | 80-120 |
| Coarse sand, poorly sorted | 80-120 |
| Coarse sand, well sorted, clean | 120-150 |

(Fetter, 2001)

*K Analysis from Sieves*

Sieve tests were conducted on samples collected from two monitoring wells, MW18Y and MW19Y, at Site 11. Sediment from Site 11 consists primarily of fine to medium grained sand. A uniformity coefficient ($C_u$) was calculated for both monitoring wells. The $C_u$ for well MW18Y was 2.7 and the $C_u$ for well MW19Y was 3.3. This sample is considered well sorted because the $C_u$ value is less than 4. The Hazen method was used to calculate the hydraulic conductivity for Site 11. A C value of 80-120 was used because the sample is medium well sorted sand. The values used for the calculations can be seen in Table 3-4. The average of the three hydraulic conductivities was 8.64 m/day for well MW18Y and 4.96 m/day for well MW19Y.

Well: MW18Y

| mm | Phi | Tare (g) | Wt. (g) | Corrected Weight | Cumul. Wt. (g) | Cumul. Wt % | Percent finer by weight |
|---|---|---|---|---|---|---|---|
| 2 | -1 | 2.54 | 2.63 | 0.09 | 0.09 | 0.30 | 99.70 |
| 1.68 | -0.75 | 2.53 | 2.59 | 0.06 | 0.15 | 0.50 | 99.50 |
| 1.41 | -0.5 | 2.35 | 2.52 | 0.17 | 0.32 | 1.08 | 98.92 |
| 1.19 | -0.25 | 2.51 | 2.66 | 0.15 | 0.47 | 1.58 | 98.42 |
| 1 | 0 | 2.2 | 2.36 | 0.16 | 0.63 | 2.12 | 97.88 |
| 0.84 | 0.25 | 2.39 | 2.72 | 0.33 | 0.96 | 3.23 | 96.77 |
| 0.71 | 0.5 | 2.35 | 2.54 | 0.19 | 1.15 | 3.87 | 96.13 |
| 0.59 | 0.75 | 2.31 | 2.63 | 0.32 | 1.47 | 4.95 | 95.05 |
| 0.5 | 1 | 2.24 | 2.51 | 0.27 | 1.74 | 5.85 | 94.15 |
| 0.42 | 1.25 | 2.47 | 3.14 | 0.67 | 2.41 | 8.11 | 91.89 |
| 0.35 | 1.5 | 2.27 | 3.86 | 1.59 | 4 | 13.46 | 86.54 |
| 0.3 | 1.75 | 2.45 | 7.37 | 4.92 | 8.92 | 30.01 | 69.99 |
| 0.25 | 2 | 2.42 | 9.07 | 6.65 | 15.57 | 52.39 | 47.61 |
| 0.21 | 2.25 | 2.37 | 8.16 | 5.79 | 21.36 | 71.87 | 28.13 |
| 0.177 | 2.5 | 2.51 | 5.19 | 2.68 | 24.04 | 80.89 | 19.11 |
| 0.149 | 2.75 | 2.75 | 3.35 | 0.6 | 24.64 | 82.91 | 17.09 |
| 0.125 | 3 | 2.58 | 3.59 | 1.01 | 25.65 | 86.31 | 13.69 |
| 0.105 | 3.25 | 2.56 | 3.41 | 0.85 | 26.5 | 89.17 | 10.83 |
| 0.088 | 3.5 | 2.4 | 3.47 | 1.07 | 27.57 | 92.77 | 7.23 |
| 0.074 | 3.75 | 2.27 | 3.09 | 0.82 | 28.39 | 95.52 | 4.48 |
| 0.0625 | 4 | 2.54 | 2.89 | 0.35 | 28.74 | 96.70 | 3.30 |
| 0.01 | >4 | 2.38 | 3.36 | 0.98 | 29.72 | 100.00 | 0.00 |

Table I: Results of sieve test on sediment from well MW18Y.

Well MW19Y

| mm | Phi | Tare (g) | Wt. (g) | Corrected Weight | Cumul. Wt. (g) | Cumul. Wt % | Percent finer by weight |
|---|---|---|---|---|---|---|---|
| 2 | -1 | 2.54 | 2.55 | 0.01 | 0.01 | 0.03 | 99.97 |
| 1.68 | -0.75 | 2.53 | 0 | 0 | 0.01 | 0.03 | 99.97 |
| 1.41 | -0.5 | 2.35 | 2.4 | 0.05 | 0.06 | 0.18 | 99.82 |
| 1.19 | -0.25 | 2.51 | 2.63 | 0.12 | 0.18 | 0.54 | 99.46 |
| 1 | 0 | 2.2 | 2.41 | 0.21 | 0.39 | 1.17 | 98.83 |
| 0.84 | 0.25 | 2.39 | 2.78 | 0.39 | 0.78 | 2.35 | 97.65 |
| 0.71 | 0.5 | 2.35 | 2.77 | 0.42 | 1.2 | 3.61 | 96.39 |
| 0.59 | 0.75 | 2.31 | 3.03 | 0.72 | 1.92 | 5.78 | 94.22 |
| 0.5 | 1 | 2.24 | 2.79 | 0.55 | 2.47 | 7.43 | 92.57 |
| 0.42 | 1.25 | 2.47 | 3.6 | 1.13 | 3.6 | 10.83 | 89.17 |
| 0.35 | 1.5 | 2.27 | 4.18 | 1.91 | 5.51 | 16.58 | 83.42 |
| 0.3 | 1.75 | 2.45 | 7.55 | 5.1 | 10.61 | 31.93 | 68.07 |
| 0.25 | 2 | 2.42 | 7.77 | 5.35 | 15.96 | 48.03 | 51.97 |
| 0.21 | 2.25 | 2.37 | 7.85 | 5.48 | 21.44 | 64.52 | 35.48 |
| 0.177 | 2.5 | 2.51 | 6.2 | 3.69 | 25.13 | 75.62 | 24.38 |
| 0.149 | 2.75 | 2.75 | 3.73 | 0.98 | 26.11 | 78.57 | 21.43 |
| 0.125 | 3 | 2.58 | 3.9 | 1.32 | 27.43 | 82.55 | 17.45 |
| 0.105 | 3.25 | 2.56 | 3.38 | 0.82 | 28.25 | 85.01 | 14.99 |
| 0.088 | 3.5 | 2.4 | 3.36 | 0.96 | 29.21 | 87.90 | 12.10 |
| 0.074 | 3.75 | 2.27 | 3.07 | 0.8 | 30.01 | 90.31 | 9.69 |
| 0.0625 | 4 | 2.54 | 2.97 | 0.43 | 30.44 | 91.60 | 8.40 |
| 0.01 | >4 | 2.44 | 5.23 | 2.79 | 33.23 | 100.00 | 0.00 |

Table II: Results of sieve test on sediment from well MW19Y.

| Well | d10 (mm) | d60 (mm) |
|---|---|---|
| MW18Y | 0.1 | 0.27 |
| MW19Y | 0.075 | 0.25 |
| | | |
| **Well** | **C** | **K (m/day)** |
| MW18Y | 80 | 6.91 |
| MW18Y | 100 | 6.84 |
| MW18Y | 120 | 10.37 |
| MW19Y | 80 | 3.89 |
| MW19Y | 100 | 4.86 |
| MW19Y | 120 | 5.83 |

Table III: Calculations performed for the determination of hydraulic conductivity based on sieve analysis.

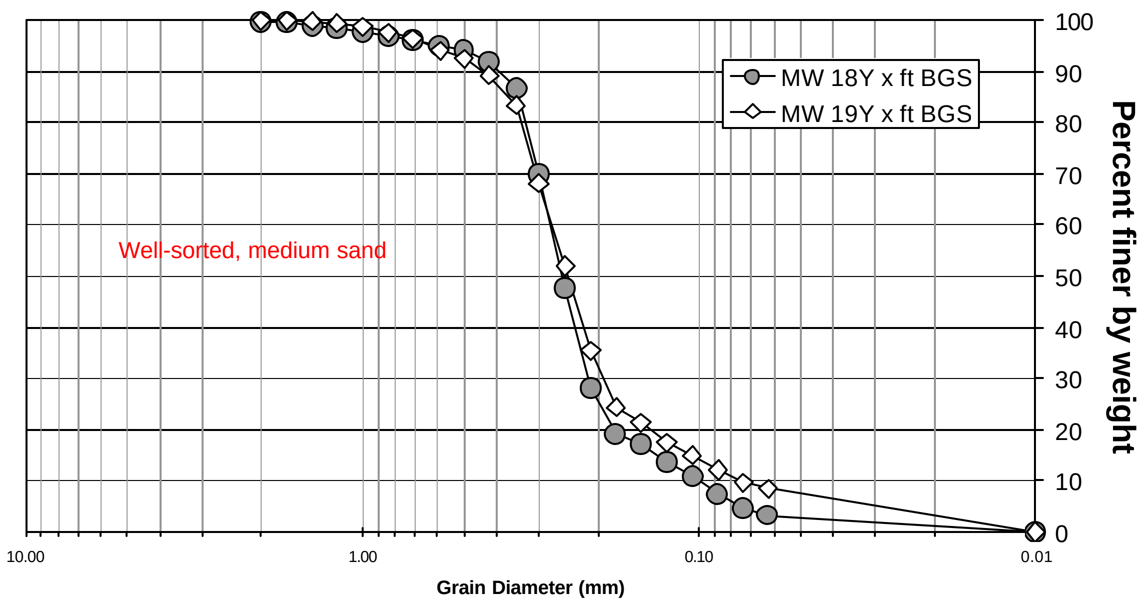


Figure I: Results of sieve test on wells MW18Y and MW19Y.

*Determination of Hydraulic Conductivity at Site 11 with Slug Tests*

*Slug Test Method*

A slug test can be performed in a small diameter monitoring well. This type of test can be used to determine the hydraulic conductivity of the formation in close proximity to a monitoring well. A known volume of water is quickly added to the monitoring well and the rate at which the water level falls or rises is measured. This data is then analyzed.

One method to analyze slug test data is the Bouwer and Rice Slug-Test method. This test can be performed on open boreholes or fully or partially penetrating screened wells. The Bouwer-Rice equation is:

$$K = \frac{r_c^2 \ln\left(R_e / R\right)}{2L_e} \frac{1}{t} \ln\left(\frac{H_0}{H_t}\right)$$

where K is hydraulic conductivity (m/d), $r_c$ is the radius of the well casing (m), R is the radius of the gravel envelope (m), $R_e$ is the effective radial distance over which head is dissipated (m), $L_e$ is the length of the screen or open section of the well through which water can enter (m), $H_0$ is the drawdown at t = 0 (m), $H_t$ is the drawdown at time t = t (m), and t is the time since $H = H_0$ (d)

*K Analysis from Slug Tests*

Slug tests were performed on Well E6 at site 11. A slug of 11.4 L of water was nearly instantaneously added to E6, which is central to the treatment zone. After the slug was added, the water level was monitored for 35 minutes for two tests and 10 minutes for a third test (see Tables IV through VI). To compute the hydraulic conductivity, the data was imported into Aqtesolv and computed using the Bouwer-Rice slug test method. The following values based on the construction of the well E6 were used in the program Aqtesolv. The results from the slug test showed that the hydraulic conductivity of the Columbia aquifer was 0.69 m/day for slug test 1, 0.71 m/day for slug test 2, and 0.76 m/day for slug test 3.

| Slug test | Slug test 1 | Slug test 2 | Slug test 3 |
|---|---|---|---|
| Aquifer saturated thickness | 4.1 m | 4.1 m | 4.1 m |
| Initial water level displacement | 0.96 m | 1.85 m | 1.91 m |
| Static water column height | 4.4 m | 4.4 m | 4.4 m |
| Casing radius | 0.057 m | 0.057 m | 0.057 m |
| Effective well radius | 0.28 m | 0.28 m | 0.28 m |
| Screen length | 1.52 m | 1.52 m | 1.52 m |
| Total well penetration depth | 4.4 m | 4.4 m | 4.4 m |
| Effective porosity of sand filter pack envelope | 0.5 | 0.5 | 0.5 |

| Time (min) | Time (sec) | Water Level 1 (m) | Displacement 1 (m) |
|---|---|---|---|
| 0.00 | 0 | 1.87 | 0 |
| 0.17 | 10 | 0.67 | 1.2 |
| 0.33 | 20 | 0.74 | 1.13 |
| 0.50 | 30 | 0.78 | 1.09 |
| 0.67 | 40 | 0.83 | 1.04 |
| 0.83 | 50 | 0.88 | 0.99 |
| 1.00 | 60 | 0.93 | 0.94 |
| 1.25 | 75 | 0.99 | 0.88 |
| 1.50 | 90 | 1.045 | 0.825 |
| 2.00 | 120 | 1.145 | 0.725 |
| 2.50 | 150 | 1.23 | 0.64 |
| 3.00 | 180 | 1.31 | 0.56 |
| 3.50 | 210 | 1.375 | 0.495 |
| 4.00 | 240 | 1.435 | 0.435 |
| 5.00 | 300 | 1.53 | 0.34 |
| 6.00 | 360 | 1.595 | 0.275 |
| 7.00 | 420 | 1.65 | 0.22 |
| 8.00 | 480 | 1.7 | 0.17 |
| 9.00 | 540 | 1.73 | 0.14 |
| 10.00 | 600 | 1.75 | 0.12 |
| 11.00 | 660 | 1.77 | 0.1 |
| 13.00 | 780 | 1.8 | 0.07 |
| 15.00 | 900 | 1.82 | 0.05 |
| 17.00 | 1020 | 1.83 | 0.04 |
| 20.00 | 1200 | 1.84 | 0.03 |
| 25.00 | 1500 | 1.85 | 0.02 |
| 30.00 | 1800 | 1.85 | 0.02 |
| 35.00 | 2100 | 1.85 | 0.02 |

Table IV: Results from slug test before well development.

| Time (min) | Time (sec) | Water Level 2 (m) | Displacement 2 (m) |
|---|---|---|---|
| 0.00 | 0 | 1.85 | 0 |
| 0.17 | 10 | 0.6 | 1.25 |
| 0.33 | 20 | 0.67 | 1.18 |
| 0.50 | 30 | 0.75 | 1.1 |
| 0.67 | 40 | 0.79 | 1.06 |
| 0.83 | 50 | 0.84 | 1.01 |
| 1.00 | 60 | 0.88 | 0.97 |
| 1.25 | 75 | 0.95 | 0.9 |
| 1.50 | 90 | 1.01 | 0.84 |
| 2.00 | 120 | 1.115 | 0.735 |
| 2.50 | 150 | 1.205 | 0.645 |
| 3.00 | 180 | 1.285 | 0.565 |
| 3.50 | 210 | 1.355 | 0.495 |
| 4.00 | 240 | 1.41 | 0.44 |
| 5.00 | 300 | 1.51 | 0.34 |
| 6.00 | 360 | 1.58 | 0.27 |
| 7.00 | 420 | 1.635 | 0.215 |
| 8.00 | 480 | 1.68 | 0.17 |
| 9.00 | 540 | 1.715 | 0.135 |
| 10.00 | 600 | 1.74 | 0.11 |
| 11.00 | 660 | 1.755 | 0.095 |
| 13.00 | 780 | 1.79 | 0.06 |
| 15.00 | 900 | 1.805 | 0.045 |
| 17.00 | 1020 | 1.82 | 0.03 |
| 20.00 | 1200 | 1.825 | 0.025 |
| 25.00 | 1500 | 1.83 | 0.02 |
| 30.00 | 1800 | 1.84 | 0.01 |
| 35.00 | 2100 | 1.845 | 0.005 |

Table V: Results from slug test 2 before well development.

| Time (min) | Time (sec) | Water Level 3 (m) | Displacement 3 (m) |
|---|---|---|---|
| 0.00 | 0 | 1.905 | 0 |
| 0.25 | 15 | 0.65 | 1.255 |
| 0.50 | 30 | 0.71 | 1.195 |
| 0.75 | 45 | 0.82 | 1.085 |
| 1.00 | 60 | 0.885 | 1.02 |
| 1.50 | 90 | 1.02 | 0.885 |
| 2.00 | 120 | 1.13 | 0.775 |
| 2.50 | 150 | 1.23 | 0.675 |
| 3.00 | 180 | 1.315 | 0.59 |
| 3.50 | 210 | 1.395 | 0.51 |
| 4.00 | 240 | 1.455 | 0.45 |
| 5.00 | 300 | 1.59 | 0.315 |
| 6.00 | 360 | 1.69 | 0.215 |
| 7.00 | 420 | 1.7 | 0.205 |
| 8.00 | 480 | 1.745 | 0.16 |
| 9.00 | 540 | 1.785 | 0.12 |
| 10.00 | 600 | 1.81 | 0.095 |

Table VI: Results from slug test 3 after well development.

# Appendix V:
# Theory and Tracer Selection Process for Partition Tracer Testing

During a PTT, a suite of conservative and partitioning tracers are injected into one or more injection wells, and are subsequently recovered from one or more extraction wells. By definition, the transport of conservative tracers is unaffected by the presence of NAPL in the tracer sweep zone. However, the partitioning tracers will temporarily partition into any accessible NAPL, and will therefore be retarded relative to the transport of the conservative tracers. The retardation (R) a partitioning tracers is determined from the observed tracer breakthrough curve (BTC) at the extraction wells and is defined by:

$$R = \frac{\overline{t_p}}{\overline{t_c}} \qquad (1)$$

where $\overline{t_p}$ and $\overline{t_c}$ are the mean travel times for the partitioning and conservative tracers. The tracer travel times are determined directly from the observed BTCs by temporal moment analysis. When the tracer input is constant over a finite period of time ($t_s$), the mean tracer ($\bar{t}$) travel time is given by:

$$\bar{t} = \frac{\int t \cdot C(t)dt}{\int C(t)dt} - \frac{t_s}{2} \qquad (2)$$

where $t$ is the measurement time and $C(t)$ is the tracer concentration over time at the extraction well (i.e., the tracer BTC). Typically, BTCs from field PTTs exhibit significant tailing, which is primarily caused by the hydraulics of the injection/extraction system. Truncation of this tail region due to early test termination can lead to moment estimation errors; therefore, an exponential extrapolation method (i.e., Helms 1997) was used model tracer BTC beyond test cutoff in order to improve moment estimates of the BTCs.

For a system where all of the pore space is occupied by either water or NAPL, the pore-space NAPL saturation ($S_N$) is calculated by (see Jin, 1995):

$$S_N = \frac{R-1}{R+K_{NW}-1} \qquad (3a)$$

and

$$K_{NW} = \frac{C_N}{C_W} \qquad (3b)$$

where $K_{NW}$ is the tracer-specific partition coefficient typically determined in laboratory batch tests ($C_N$ and $C_W$ represent the tracer concentrations in the NAPL and water at equilibrium).

Partitioning tracer tests were conducted at the site before (Pre-PTT) and after (Post-PTT) remediation activities. The two primary purposes of the Pre-PTT were: (1) to estimate initial $S_N$ and total NAPL volume in the treatment zone, and (2) generally identify any subregions within the treatment zone with higher NAPL saturation. The Post-PTT was designed primarily to verify contaminant mass removal estimated from effluent concentrations during remediation. The following sections provide a description of the general PTT design, observed field results, and an analysis and interpretation of test data.

**PTT Design and Field Methods**

Conceptually, PTT application is relatively simple; however, successful field implementation requires careful design to optimize test results while balancing budget, labor, and other practical constraints. For example, some of the primary test design specifications that need to be considered include:

- Dimensions of the tested subsurface volume,
- Number and locations of injection and extraction wells,
- Injection and extraction rates,
- Necessity of additional hydraulic control wells,
- Tracer test duration,
- Sampling frequency,
- Tracer suite,
- Tracer concentrations and acceptable detection limits,
- Volume of tracer pulse, and,
- Extraction water treatment and disposal.

Additionally, the specifications of the various physical components required for the PTT (injection/extraction wells, pumps, storage tanks, effluent treatment system, etc.) should be consistent with the operational requirements associated with the remediation activity. For example, PTT injection/extraction wells were located and constructed so they could be utilized for both the PTTs and the cyclodextrin flushing. The following sections describe the PTT design process and provide specifics about the test.

*Tracer Suite Selection*

Theoretically, only one conservative tracer and one partitioning tracer are necessary to estimate $S_N$. However, a suite of multiple partitioning tracers is typically used in field applications, since the range of probable $S_N$ values estimated before a PTT values is typically very large. If the tracer suite is chosen appropriately, it can provide redundancy and while also increasing the likelihood that optimize tracer separation will be observed for several tracers, regardless of the actual $S_N$.

Based on the results of the numerical modeling, the optimal partitioning tracer retardation was estimated to be between 1.2 and 1.8. This range was anticipated to provide sufficient separation from the conservative tracer BTC, while also permitting reasonable tracer mass recovery over the anticipated PTT duration. Since targeted DNAPL-zone soil sampling had not been previously performed, the estimated $S_N$ value prior to the Pre-PTT was highly uncertain. Therefore, partitioning tracers were chosen for the Pre-PTT that were optimally designed to quantify $S_N$ values ranging form 1% to 10%. This is indicated by the target region in Figure I, which corresponds to partitioning tracers with target $K_{NW}$ values ranging from approximately 2 to 50.

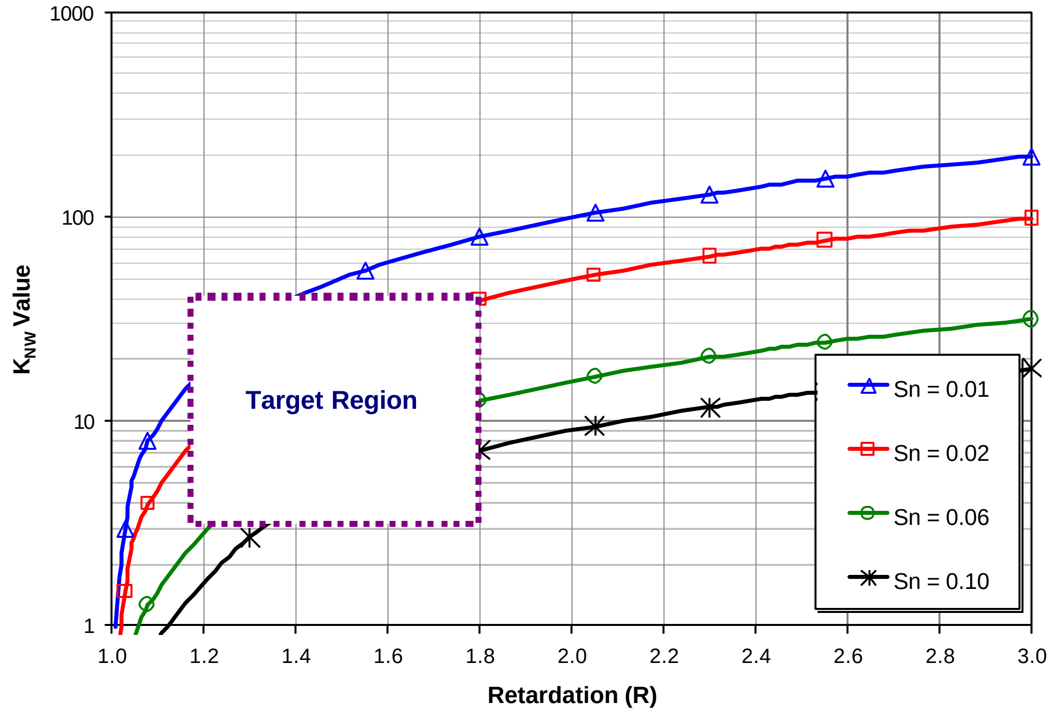


**Figure I.** Target partitioning tracer KN values based on anticipated $S_N$ range and optimal design tracer retardation.

Data from several field PTTs indicate that some alcohol partitioning tracers exhibit significant in-situ biodegradation, even during the typically short duration of the PTT . (e.g., Annable et al., 1998). However, methylated and ethylated alcohols are generally more recalcitrant that straight-chain alcohols. Therefore, these tracers were chosen as the primary tracer for a given target $K_{NW}$ value. Due to their low costs, the straight-chain alcohols hexanol and heptanol were also included; however, they were considered "secondary" tracers. The alcohol tracer suite for the Pre-PTT included: 2-methyl-1-butanol, 2-ethyl-1-butanol, 2,4-dimethyl-3-pentanol, 2-ethyl-1-hexanol, hexanol, and heptanol. The Post-PTT tracer suite included: 2-methyl-1-butanol, 4-methyl-2-pentanol, 2-ethyl-1-hexanol, and heptanol.

Commonly after a flushing-based treatment for a NAPL-zone, significant concentrations of residual remediation fluid remain in the NAPL zone (e.g., McCray and Brusseau, 1998; Lee et al., 1998; Falta et al., 1999; Jawitz et al., 2000, Battelle and Duke, 2001; Boving et al., 2002, and Vane and Yeh, 2002). In some cases, the concentrations of residual remediation fluids left in-situ after treatment were as high as 7% (Jawitz et al., 1998), and these residual fluids have the potential to modify affective $K_{NW}$ values for Post-PTT tracers. For example, Vane and Yeh (2002) report that PTT estimation error may have been caused by residual concentrations of propylene glycol. Battelle and Duke (2001) determined that data from a post-remediation PTT to be unusable due to unanticipated sorbtion to residual surfactant remediation fluid. Consequently, the influence of residual cyclodextrin on $K_{NW}$ values was investigated in batch partitioning tests prior to field work. Generally, it was determined that cyclodextrin lowers the apparent $K_{NW}$ for some alcohol tracers. However, as shown in Figure 8, there is an apparent maximum affect, and the effective $K_{NW}$ values can be predicted from empirical models. The results of these experiments are presented in detail in Dugan et al. (2003), and this influence on $K_{NW}$ values was accounted for in the PTT analyses.

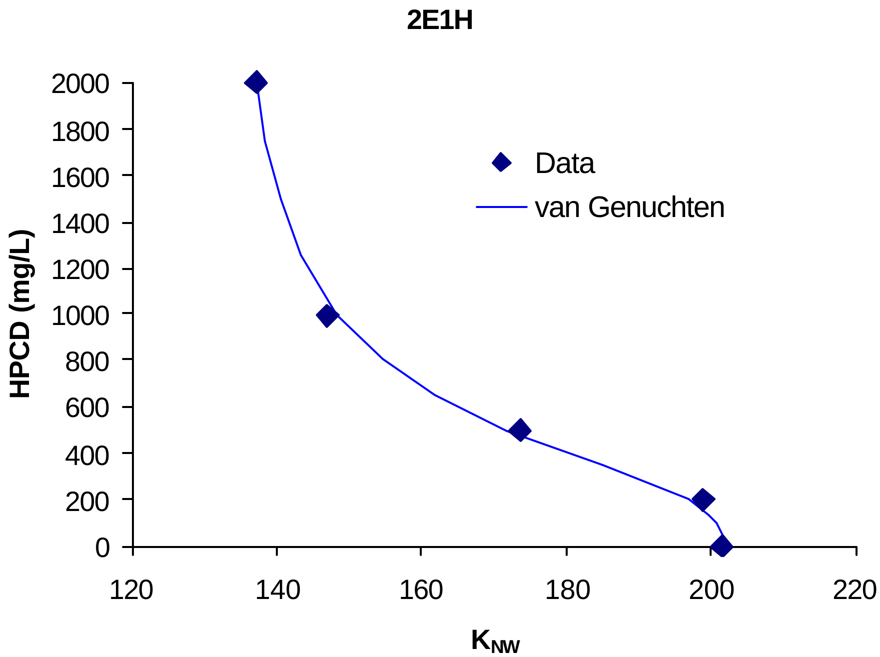


**Figure II.** Influence of residual cyclodextrin on effective KNW values for 2-ethyl-1-hexanol (2E1H). From Dugan et al., 2003.

Alcohols have been used as partitioning tracers for the majority of field PTTs; however, Divine (2000) investigated the applicability of dissolved helium and neon partitioning tracer in the laboratory because they exhibit some notable advantages compared to alcohol tracers. For example, they are non-biodegradable, nontoxic, do not sorb to aquifer materials, and have low analytical detection limits. Divine (2000) reported successful batch partitioning tests and column-scale PTTs using these tracers and recommended field application of these tracers along with previously-used alcohol tracers. Therefore, dissolved helium and neon were included in the Pre- and Post-PTT tracer suites, respectively.

In addition to the partitioning tracers, bromide ($Br^-$) was included in the tracer suite as a conservative tracer. While NAPL saturation can be calculated directly from the transport of two partitioning tracers using a more general form of Equation 3a (i.e., a conservative tracer is unnecessary), it is generally beneficial to include a conservative tracer since it provides a direct measure of actual fluid velocity. Additionally, $Br^-$ is relatively inexpensive and can be measured in the field with an ion selective electrode. A list of the conservative and partitioning tracers used in the PTTs, along with their respective effective $K_{NW}$ values, are included in Table I.

| Pre-PTT | | Post-PTT | |
|---|---|---|---|
| Tracer | $K_{NW}$ | Tracer | Effective $K_{NW}$ |
| Bromide | 0.0 | Bromide | 0.0 |
| Helium | 2.42[a] | Neon | 3.24[a] |
| 2-methyl-1-butanol | 3.71[b] | 2-methyl-1-butanol | 3.38[b] |
| 2-ethyl-1-butanol | 13.4[b] | 4-methyl-2-pentanol | 9.66[b] |
| hexanol | 18.6[d] | 2-ethyl-1-hexanol | 131[a] |
| 2,4-dimethyl-3-pentanol | 71.3[b] | heptanol | 163.1[c] |
| heptanol | 163.1[c] | | |
| 2-ethyl-1-hexanol | 202[a] | | |

Sources
[a]Divine et al. 2003
[b]Dugan et al. 2003
[c]Young et al. 1999
[d]Wang et al. 1998

**Table I.** Final tracer suite for the field PTTs with $K_{NW}$ values. Note effective $K_{NW}$ values for Post-PTT partitioning tracers are based on results presented in Dugan et al. (2003).

**Sample Collection and Analysis**

Tracer samples were collected from in-line effluent sampling ports at pre-determined time intervals based on the results of the numerical models. Early in the tests, samples were collected every 30 minutes to ensure accurate characterization of the BTC peak, while late in the tests when the changes in tracer concentrations were small, samples were collected every couple of hours. The sampling frequency was confirmed real-time in the field by observed changes in the specific conductance of extraction fluids.

Samples were analyzed for bromide with an ISE in the field within approximately 2 weeks of collection. Samples collected for alcohol tracers were placed in coolers and shipped to the University of Arizona for analysis (see demonstration plan for a description analytical methods). Water samples were analyzed for dissolved helium and neon with a field GC (Schimadzu 8A) by a direct headspace analysis method similar to the method described by Divine (2000).

# Appendix VI:
## Actual Demonstration Cost

### Cyclodextrin Enhanced Flushing at Naval Amphibious Base Little Creek, VA

### CAPITAL COST (actual cost of demonstration)

**Assumptions**

Flushing Vol): 9.0 m3
Soil mass: 49.3 tons

PI : Principal Investigator

Power Consumption in: KW
Cost / KWH $ 0.05725
Note: Most electrical power was provided by generators.

Number of wells, type and depth needed for remediation
3 injection wells (22.5 ft)
3 extraction wells (22.5 ft)
2 hydraulic control wells (22.5 ft)

**Development Study (Cyclodextrin Selection)**

Studies were carried out for demonstration purposes - not required for commercial CDEF application

| Units | No of units | Unit labor cost (hr) | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $16,599.00 | $ 1,440 | $ 16,599 | $ 1,440 | $ 18,039 | | | Lab techician (grad. Student) |
| EA | 1 | $ 5,213.00 | $ - | $ 5,213 | $ - | $ 5,213 | | | Senior Geochemist (PI) |
| EA | 1 | $ - | $ 5,600 | $ - | $ 5,600 | $ 5,600 | | | Lab equipment |
| EA | 1 | $ - | $ 3,000 | $ - | $ 3,000 | $ 3,000 | | | Report preparation (PI) |
| | | | | | | | **$ 31,852** | | **Total Cyclodextrin Selection** |

**Bench Scale Treatment Equipment Testing**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 2,550 | $ - | $ 2,550 | $ 2,550 | | | Membrane selection, testing, and equipment |
| EA | 1 | $10,309.00 | $ - | $ 10,309 | $ - | $ 10,309 | | | Lab techician (grad. Student) |
| EA | 1 | $ - | $ 7,200 | $ - | $ 7,200 | $ 7,200 | | | Lab equipment |
| EA | 1 | $ - | $ 3,000 | $ - | $ 3,000 | $ 3,000 | | | Report preparation |
| | | | | | | | **$ 23,059** | | **Total Bench Scale Treatment Equipment Testing** |

**OPTIONAL Pre-trial Partition Tracer Test (PTT)**

PTT is optional and was carried out for performance evaluation purposes only

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ 6,397.00 | $ - | $ 6,397 | $ - | $ 6,397 | | | Pre-treatment site characterization (hydrauylic and transport modeling) (Co-PI) |
| EA | 1 | $ 6,687.00 | $ - | $ 6,687 | $ - | $ 6,687 | | | Tracer selection testing (lab) (grad student) |
| EA | 1 | $24,038.00 | $ - | $ 24,038 | $ - | $ 24,038 | | | Lab techician (grad student) |
| EA | 1 | $ - | $ 8,700 | $ - | $ 8,700 | $ 8,700 | | | Tracer (alcohols and gases) |
| EA | 1 | $24,610.00 | $ - | $ 24,610 | $ - | $ 24,610 | | | Field lab technician (grad student) |
| EA | 1 | $ - | $ 700 | $ - | $ 700 | $ 700 | | | Specialized injection/collection equipment |
| EA | 1 | $ - | $ 2,970 | $ - | $ 2,970 | $ 2,970 | | | Field supplies |
| EA | 1 | $ - | $ 4,725 | $ - | $ 4,725 | $ 4,725 | | | Travel and subsidence at field site |
| EA | 1 | $ 8,032 | $ - | $ 8,032 | $ - | $ 8,032 | | | Chemical analysis (alcohol tracers) |
| EA | 1 | $ - | $ 100 | $ - | $ 100 | $ 100 | | | License for PTT (to Duke Eng.) |
| | | | | | | | **$ 86,959** | | **Total Pre-trial Partition Tracer Test (PTT)** |

**OPTIONAL Post-trial Partition Tracer Test (PTT)**

PTT is optional and was carried out for performance evaluation purposes only

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 8,700 | $ - | $ 8,700 | $ 8,700 | | | Tracer (alcohols and gases) |
| EA | 1 | $19,032.00 | $ - | $ 19,032 | $ - | $ 19,032 | | | Field lab technician (grad student) |
| EA | 1 | $ - | $ 2,970 | $ - | $ 2,970 | $ 2,970 | | | Field supplies |
| EA | 1 | $ - | $ 4,725 | $ - | $ 4,725 | $ 4,725 | | | Travel and subsidence at field site |
| EA | 1 | $ - | $ 22,753 | $ - | $ 22,753 | $ 22,753 | | | Report preparation (Co-PI) |
| EA | 1 | $ 8,032 | $ - | $ 8,032 | $ - | $ 8,032 | | | Chemical analysis (alcohol tracers) |
| | | | | | | | **$ 66,212** | | **Total Post-trial Partition Tracer Test (PTT)** |

**DNAPL Source Zone Characterization**

Approximate extent of plume was already known prior to demonstration.

| Units | No of units | Unit labor cost (hr) | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 1,600 | $ - | $ 1,600 | $ 1,600 | | | Mob/Demob Geoprobe/Membrane Interface Probe (MIP) |
| EA | 2 | $ - | $ 3,500 | $ - | $ 7,000 | $ 7,000 | | | MIP with Electrical Conductivity |
| EA | 5 | $ 95.00 | $ - | $ 475 | $ - | $ 475 | | | Operator per diem |
| EA | 2 | $ - | $ 1,250 | $ - | $ 2,500 | $ 2,500 | | | In Situ GW/Soil sampling |
| EA | 15 | $ - | $ 126 | $ - | $ 1,890 | $ 1,890 | | | Lab Analysis (TCL Volatile Organic Compound) |
| EA | 60 | $ 50.00 | $ - | $ 3,000 | $ - | $ 3,000 | | | Labor (2 Person Field Crew) |
| EA | 3 | $ - | $ 200 | $ - | $ 600 | $ 600 | | | Equipment and Expendables |
| | | | | | | | **$ 17,065** | | **Total DNAPL Source Zone Characterization (in-kind contribution)** |

**Treatability Study (Site soil testing)**

| Units | No of units | Unit labor cost (hr) | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $10,696.00 | $ - | $ 10,696 | $ - | $ 10,696 | | | Lab techician (soil column tests) |
| EA | 1 | $ - | $ 2,550 | $ - | $ 2,550 | $ 2,550 | | | Lab equipment |
| EA | 1 | $ - | $ 3,000 | $ - | $ 3,000 | $ 3,000 | | | Report preparation |
| | | | | | | | **$ 16,246** | | **Total Cyclodextrin Selection** |

## Engineering, Design, and Modeling

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $17,983.00 | $ 1,770 | $ 22,000 | $ 1,770 | $ 23,770 | | | Work Plan, H&S plan, Site Management Plan (Project leader) |
| EA | 1 | $ - | $ 2,500 | $ - | $ 2,500 | $ 2,500 | | | Permits and licences, estimated (in-kind contribution) |
| | | | | | | | **$ 26,270** | **Total Engineering, Design, and Modeling** | |

## Technology Mobilization, Setup, and Demobilization

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 21,911 | $ - | $ 21,911 | $ 21,911 | | | Travel to and from site (incl. accommodation) |
| | | | | | | | **$ 21,911** | **Total Performance Assessment** | |

## Site Work

### *Site Set-up*

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 1,000 | $ - | $ 1,000 | $ 1,000 | | | Secondary containment (berm) |
| EA | 1 | $ - | $ 1,450 | $ - | $ 1,400 | $ 1,400 | | | Electricity hook-up (in-kind contribution) |
| EA | 80 | $ 50.00 | $ - | $ 4,000 | $ - | $ 4,000 | | | Plumbing (temporary) |
| EA | 1 | $ - | $ 193 | $ - | $ 193 | $ 193 | | | On-site sanitary installations |
| | | | | | | | **$ 6,593** | **Total Site Set-up** | |

## Equipment and Appurtenances

### *Well Field Installation*

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| ft | 177 | $ - | $ 77 | $ - | $ 13,576 | $ 13,576 | | | Injection/Extraction well installation |
| EA | 1 | $ - | $ 552 | $ - | $ 552 | $ 552 | | | Grunfos submersible pumps (Model 5S) |
| EA | 4 | $ - | $ 552 | $ - | $ 2,208 | $ 2,208 | | | Grunfos submersible pumps (Model 5S) (in-kind) |
| | | | | | | | **$ 16,336** | **Total Well Installation** | |

### *Above Ground Plumbing*

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| ft | 500 | $ - | $ 2 | $ - | $ 900 | $ 900 | | | Well piping, 3/4 in PVC and flex tubing |
| EA | 8 | $ - | $ 78 | $ - | $ 624 | $ 624 | | | Flowmeters |
| EA | 16 | $ - | $ 20 | $ - | $ 320 | $ 320 | | | Flow control valves |
| EA | 12 | $ - | $ 45 | $ - | $ 540 | $ 540 | | | In-line sample ports |
| EA | 4 | $ - | $ 294 | $ - | $ 1,176 | $ 1,176 | | | Transfer pumps |
| ft | 150 | $ - | $ 2 | $ - | $ 270 | $ 270 | | | Waste water disposal piping, 3/4 in flex tubing |
| ft | 60 | $ - | $ 9 | $ - | $ 516 | $ 516 | | | Connection of air stripper (6 in PVC) |
| hrs | 24 | $ 50.00 | $ - | $ 1,200 | $ - | $ 1,200 | | | Plumbing air stripper and off-gas treatment train (in kind) |
| | 1 | $ - | $ 400 | $ - | $ 400 | $ 400 | | | Connection of UF |
| | 1 | $ - | $ 980 | $ - | $ 980 | $ 980 | | | Connection of Pervap |
| EA | 1 | $ - | $ 36 | $ - | $ 36 | $ 36 | | | Pressure transducer (injection wells) |
| | | | | | | | **$ 6,962** | **Total Above Ground Piping** | |

### *Demobilization*

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 14,464 | $ - | $ 14,464 | $ 14,464 | | | Freight (Palletizing, loading, and shipping of equipmemt) |
| | | | | | | | **$ 14,464** | **Total Demobilization** | |

## Startup and Testing

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| hrs | 96 | $ 50.00 | $ - | $ 4,800 | $ - | $ 4,800 | | | Operator Training (6 people field crew) |
| hrs | 210 | $ 50.00 | $ - | $ 10,500 | $ - | $ 10,500 | | | System shake-down, well testing, etc. |
| | | | | | | | **$ 15,300** | **Total Startup and Testing** | |

## Other (non-process related)

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 4,800 | $ - | $ 4,800 | $ 4,800 | | | Office and admin. equipment (computer, printer, etc) |
| EA | 3 | $ - | $ 550 | $ - | $ 1,650 | $ 1,650 | | | H&S training (OSHA) |
| EA | 1 | $ - | $ 1,600 | $ - | $ 1,600 | $ 1,600 | | | Field safety equipment, various |
| | | | | | | | **$ 8,050** | **Total Other** | |

| | |
|---|---|
| $ 124,823 | CDEF Technology |
| $ 24,373 | In-kind contributions |
| $ 54,911 | Demo related studies (one-time studies) |
| $ 153,171 | Optional PTTs |
| **$ 357,278** | **Total Direct Capital** |
| | |
| $ 90,658 | Overhead and Administration |
| $ - | Contingency |
| **$ 90,658** | **Total Indirect Capital** |
| | |
| **$ 447,937** | **TOTAL CAPITAL** |

## OPERATING AND MAINTENANCE COST (actual cost of demonstration)

### Labor

Assume: 2 person per shift, 3 shifts a day, 7 days/week
Note: Labor cost based on student salaries.

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| hrs | 1900 | $ 10.00 | $ - | $ 19,000 | $ - | $ 19,000 | | Operating labor |
| hrs | 3860 | $ 10.00 | $ - | $ 38,600 | $ - | $ 38,600 | | Monitoring labor |
| hrs | 600 | $ 24.50 | $ - | $ 14,700 | $ - | $ 14,700 | | Supervision (PI and Co-PI's) |
| | | | | | | | **$ 72,300** | **Total Labor Cost** |

### Materials

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| LB | 14000 | $ - | $ 1.75 | $ - | $ 24,500 | $ 24,500 | | Cyclodextrin, tech grade |
| EA | 1 | $ - | $ 13,789.00 | $ - | $ 13,789 | $ 13,789 | | Consumable supplies |
| EA | 1 | $ - | $ 10,514.00 | $ - | $ 10,514 | $ 10,514 | | Corrective maintenance |
| | | | | | | | **$ 38,289** | **Total Material Cost** |

### Utilities and Fuel

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| KWH | 22651 | $ - | $ 0.05725 | $ - | $ 1,297 | $ 1,297 | | Electricity cost (in-kind) |
| gal | 1224 | $ - | $ 2.00 | $ - | $ 2,448 | $ 2,448 | | Fuel |
| 1000 gal | 91 | $ - | $ 0.44 | $ - | $ 40 | $ 40 | | Water (in-kind) |
| | | | | | | | **$ 3,785** | **Total Utilities and Fuel Cost** |

### Equipment Ownership and Rental

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 10,101 | $ - | $ 10,101 | $ 10,101 | | Air stripper incl. blower (200 cfm, purchase) |
| months | 8 | $ 449.00 | $ - | $ 3,592 | $ - | $ 3,592 | | 2 x 6,500 gal holding tank (rental) |
| months | 2 | $ 8,000.00 | $ - | $ 16,000 | $ - | $ 16,000 | | UF membrane unit for CD reconcentration (rental) |
| months | 2 | $15,000.00 | $ - | $ 30,000 | $ - | $ 30,000 | | PVP unit for VOC treatment (rental) |
| EA | 1 | $ - | $ 16,979 | $ - | $ 16,979 | $ 16,979 | | 4000 lbs air activated carbon filter system (rental) |
| months | 4 | $ 832.00 | $ - | $ 3,328 | $ - | $ 3,328 | | Suspended solid filter system (rental) |
| EA | 1 | | $ 368.00 | $ - | $ 368 | $ 368 | | 250 gal mixing tank (purchase) |
| months | 4 | $ 54.00 | $ - | $ 216 | $ - | $ 216 | | On-site sanitation (rental) |
| months | 2 | $ 5,498.00 | $ - | $ 10,996 | $ - | $ 10,996 | | Diesel electric generator (480 V, 350KW) (rental) |
| months | 1 | $ 1,497.00 | $ - | $ 1,497 | $ - | $ 1,497 | | Diesel electric generator (480 V, 22KW) (rental) |
| EA | 1 | | $ 19,835 | $ - | $ 19,835 | $ 19,835 | | TOC Analyzer for CD analysis (purchase) |
| EA | 1 | $ - | $ 10,000 | $ - | $ 10,000 | $ 10,000 | | On-site gas chromatograph, incl. accesoirs (purchase) |
| | | | | | | | **$ 122,912** | **Total Equipment Ownership and Rental Cost** |

### Performance Testing and Analysis

***Analysis Cost - off-site***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 1 | $56,325.00 | $ - | $ 56,325 | $ - | $ 56,325 | | VOC analysis (UA/URI labs) |
| | | | | | | | **$ 56,325** | **Total Performance Testing and Analysis - off site** |

***Analysis Cost - on-site***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 550 | $ - | $ 550 | $ 550 | | Miscellaneous lab supplies |
| EA | 1 | $ - | $ 1,600 | $ - | $ 1,600 | $ 1,600 | | Miscellaneous field supplies |
| | | | | | | | **$ 2,150** | **Total Performance Testing and Analysis - on site** |

### Other (non-process related)

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ 22,993 | $ 2,480 | $ 22,993 | $ 2,480 | $ 25,473 | | Final report preparation (PI) |
| EA | 1 | $ - | $ 4,496 | $ - | $ 4,496 | $ 4,496 | | PID for H&S survey, personal protective equip. |
| EA | 1 | $ - | $ 3,263 | $ - | $ 3,263 | $ 3,263 | | S/H of samples |
| | | | | | | | **$ 33,232** | Total Other (non-process related) |

| Total cost | Item description |
|---|---|
| $ 327,656 | CDEF Technology |
| $ 1,337 | In-kind contributions |
| **$ 328,993** | **Total Direct Capital** |
| $ 79,966 | Overhead and Administration |
| $ - | Contingency |
| $ 79,966 | **Total Indirect Operational** |
| **$ 408,959** | **TOTAL OPERATIONAL** |

## OTHER TECHNOLGOY SPECIFIC COSTS (actual cost of demonstration)

### Compliance Testing and Analysis

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 8 | $ - | $ 124.00 | $ - | $ 992 | $ 992 | | Compliance sampling (VOC and Copper), Reed Labs, VA |
| | | | | | | | **$ 992** | **Total Compliance Testing and Analysis** |

**Disposal of Hazardeous Waste**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 3,900 | $ - | $ 3,900 | $ 3,900 | | | Off-site disposal of drill cuttings (in-kind contribution) |
| EA | 1 | $ - | $ 600 | $ - | $ 600 | $ 600 | | | Off-site disposal of liquid wastes (in-kind contribution) |
| | | | | | | | **$ 4,500** | | **Total Disposal of Hazardeous Waste (in-kind)** |
| | | | | | | | $ 992 | | CDEF Technology |
| | | | | | | | $ 4,500 | | In-kind contributions |
| | | | | | | | **$ 5,492** | | **Total Direct Other Technol. Specific Cost** |
| | | | | | | | $ 291 | | Overhead and Administration |
| | | | | | | | $ - | | Contingency |
| | | | | | | | $ 291 | | **Total Indirect Other Technol. Specific Cost** |
| | | | | | | | **$ 5,783** | | **TOTAL OTHER TECHNOL. SPECIFIC COSTS** |

## OTHER PROJECT COSTS (actual cost of demonstration)

**Site Restoration**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 8 | $ 50.00 | $ - | $ 400 | $ - | $ 400 | | Site restoration (landscaping) |
| | | | | | | | **$ 400** | **Total Site Restoration** |
| | | | | | | | $ 400 | CDEF Technology |
| | | | | | | | $ - | In-kind contributions |
| | | | | | | | **$ 400** | **Total Direct Other ProjectCost** |
| | | | | | | | $ 117 | Overhead and Administration |
| | | | | | | | $ - | Contingency |
| | | | | | | | $ 117 | **Total Indirect Other Project Cost** |
| | | | | | | | **$ 517** | **TOTAL OTHER TECHNOL. SPECIFIC COSTS** |

## COST SUMMARY (actual cost of demonstration)

**$ 863,195 Total Cost (demonstration)**

* PTT's and demonstation specific activities not considered

**Unit Cost - Quantity of Contaminant Removed and Treated**

**25.8 Quantity of Media Removed and Treated (lbs VOC)**

**$ 33,457.17 Calculated Unit Cost ($/lbs)**

VOC removed **Basis for Quantity Treated**

**Unit Cost - Quantity of Groundwater Treated**

# Appendix VII:
## Cost of Real-World Implementation

### Cyclodextrin Enhanced Flushing at Naval Amphibious Base Little Creek, VA

### CAPITAL COST (real-world cost)

**Assumptions**

Flushing Vol): 9.0 m3
Soil mass: 49.3 tons
Treatment duration: 2 months

Power Consumption in: KW
Cost / KWH $ 0.05725
Note: Most electrical power was provided by generators.

Number of wells, type and depth needed for remediation
3 injection wells (22.5 ft)
3 extraction wells (22.5 ft)
2 hydraulic control wells (22.5 ft)

**DNAPL Source Zone Characterization**

Assume: Approximate extent of plume is known

| Units | No of units | Unit labor cost (hr) | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 1,600 | $ - | $ 1,600 | $ 1,600 | | | Mob/Demob Geoprobe/Membrane Interface Probe (MIP) |
| EA | 2 | $ - | $ 3,500 | $ - | $ 7,000 | $ 7,000 | | | MIP with Electrical Conductivity |
| EA | 5 | $ 95.00 | $ - | $ 475 | $ - | $ 475 | | | Operator per diem |
| EA | 2 | $ - | $ 1,250 | $ - | $ 2,500 | $ 2,500 | | | In Situ GW/Soil sampling |
| EA | 15 | $ - | $ 126 | $ - | $ 1,890 | $ 1,890 | | | Lab Analysis (TCL Volatile Organic Compound) |
| EA | 60 | $ 50.00 | $ - | $ 3,000 | $ - | $ 3,000 | | | Labor (2 Person Field Crew) |
| EA | 3 | $ - | $ 200 | $ - | $ 600 | $ 600 | | | Equipment and Expendables |
| | | | | | | | **$ 17,065** | | **Total DNAPL Source Zone Characterization** |

**Treatability Study (Site soil testing)**

| Units | No of units | Unit labor cost (hr) | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 120 | $ 85.00 | $ - | $ 10,200 | $ - | $ 10,200 | | | Lab techician (soil column tests) |
| EA | 1 | $ - | $ 2,550 | $ - | $ 2,550 | $ 2,550 | | | Lab equipment |
| EA | 24 | $ 125.00 | | $ 3,000 | $ - | $ 3,000 | | | Report preparation |
| | | | | | | | **$ 15,750** | | **Total Cyclodextrin Selection** |

**Engineering, Design, and Modeling**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 144 | $ 125.00 | $ 1,770 | $ 18,000 | $ 1,770 | $ 19,770 | | | Work Plan, H&S plan, Site Management Plan (Project leader) |
| EA | 1 | $ - | $ 2,500 | $ - | $ 2,500 | $ 2,500 | | | Permits and licences, estimated |
| | | | | | | | **$ 22,270** | | **Total Engineering, Design, and Modeling** |

**Technology Mobilization, Setup, and Demobilizatior**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 21,911 | $ - | $ 21,911 | $ 21,911 | | | Travel to and from site (incl. accommodation) |
| | | | | | | | **$ 21,911** | | **Total Performance Assessment** |

**Site Work**

***Site Set-up***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 1,000 | $ - | $ 1,000 | $ 1,000 | | | Secondary containment (berm) |
| EA | 1 | $ - | $ 1,450 | $ - | $ 1,400 | $ 1,400 | | | Electricity hook-up |
| EA | 80 | $ 50.00 | $ - | $ 4,000 | $ - | $ 4,000 | | | Plumbing (temporary) |
| EA | 1 | $ - | $ 193 | $ - | $ 193 | $ 193 | | | On-site sanitary installations |
| | | | | | | | **$ 6,593** | | **Total Site Set-up** |

**Equipment and Appurtenances**

***Well Field Installation***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| ft | 177 | $ - | $ 77 | $ - | $ 13,576 | $ 13,576 | | | Injection/Extraction well installation |
| EA | 5 | $ - | $ 552 | $ - | $ 2,760 | $ 2,760 | | | Grunfos submersible pumps (Model 5S) |
| EA | 1 | $ - | $ 14,800 | $ - | $ 14,800 | $ 14,800 | | | SCADA system, automated flow control |
| | | | | | | | **$ 31,136** | | **Total Well Installation** |

***Above Ground Plumbing***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| ft | 500 | $ - | $ 2 | $ - | $ 900 | $ 900 | | | Well piping, 3/4 in PVC and flex tubing |
| EA | 8 | $ - | $ 78 | $ - | $ 624 | $ 624 | | | Flowmeters |
| EA | 16 | $ - | $ 20 | $ - | $ 320 | $ 320 | | | Flow control valves |
| EA | 12 | $ - | $ 45 | $ - | $ 540 | $ 540 | | | In-line sample ports |
| EA | 4 | $ - | $ 294 | $ - | $ 1,176 | $ 1,176 | | | Transfer pumps |
| ft | 150 | $ - | $ 2 | $ - | $ 270 | $ 270 | | | Waste water disposal piping, 3/4 in flex tubing |
| ft | 60 | $ - | $ 9 | $ - | $ 516 | $ 516 | | | Connection of air stripper (6 in PVC) |
| hrs | 24 | $ 50.00 | $ - | $ 1,200 | $ - | $ 1,200 | | | Plumbing air stripper and off-gas treatment train |
| hrs | 8 | $ 50.00 | $ - | $ 400 | $ - | $ 400 | | | Connection of UF |
| EA | 1 | $ - | $ 36 | $ - | $ 36 | $ 36 | | | Pressure transducer (injection wells) |
| | | | | | | | **$ 5,982** | | **Total Above Ground Piping** |

***Demobilization***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 5,464 | $ - | $ 5,464 | $ 5,464 | | | Freight (Palletizing, loading, and shipping of equipmemt) |
| | | | | | | | **$ 5,464** | | **Total Demobilization** |

**Startup and Testing**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| hrs | 32 | $ 50.00 | $ - | $ 1,600 | $ - | $ 1,600 | | | Operator Training (2 people field crew) |
| hrs | 112 | $ 50.00 | $ - | $ 5,600 | $ - | $ 5,600 | | | System shake-down, well testing, etc. |
| | | | | | | | **$ 7,200** | | **Total Startup and Testing** |

**Other (non-process related)**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 4,800 | $ - | $ 4,800 | $ 4,800 | | | Office and admin. equipment (computer, printer, etc) |
| EA | 1 | $ - | $ 1,600 | $ - | $ 1,600 | $ 1,600 | | | Field safety equipment, various |
| | | | | | | | **$ 6,400** | | **Total Other** |
| | | | | | | | $ 121,305 | | CDEF Technology |
| | | | | | | | **$ 121,305** | | **Total Direct Capital** |
| | | | | | | | $ 39,352 | | Overhead and Administration |
| | | | | | | | $ - | | Contingency |
| | | | | | | | **$ 39,352** | | **Total Indirect Capital** |
| | | | | | | | **$ 160,657** | | **TOTAL CAPITAL** |

## OPERATING AND MAINTENANCE COST (real-world cost)

**Labor**

Assume: 2 person field crew, 8 hrs/day, 7 days/week, 2 months, SCADA technology is used

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| hrs | 320 | $ 50.00 | $ - | $ 16,000 | $ - | $ 16,000 | | Operating labor |
| hrs | 640 | $ 50.00 | $ - | $ 32,000 | $ - | $ 32,000 | | Monitoring labor |
| hrs | 60 | $ 90.00 | $ - | $ 5,400 | $ - | $ 5,400 | | Supervision |
| | | | | | | | **$ 53,400** | **Total Labor Cost** |

**Materials**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| LB | 14000 | $ - | $ 2.00 | $ - | $ 28,000 | $ 28,000 | | Cyclodextrin, tech grade |
| EA | 1 | $ - | $ 5,689.00 | $ - | $ 5,689 | $ 5,689 | | Consumable supplies |
| EA | 1 | $ - | $ 2,720.00 | $ - | $ 2,720 | $ 2,720 | | Corrective maintenance |
| | | | | | | | **$ 33,689** | **Total Material Cost** |

**Utilities and Fuel**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| KWH | 22651 | $ - | $ 0.05725 | $ - | $ 1,297 | $ 1,297 | | Electricity cost |
| gal | 1224 | $ - | $ 2.00 | $ - | $ 2,448 | $ 2,448 | | Fuel |
| 1000 gal | 91 | $ - | $ 0.44 | $ - | $ 40 | $ 40 | | Water |
| | | | | | | | **$ 3,785** | **Total Utilities and Fuel Cost** |

**Equipment Ownership and Rental**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 10,101 | $ - | $ 10,101 | $ 10,101 | | Air stripper incl. blower (200 cfm, purchase) |
| months | 4 | $ 449.00 | $ - | $ 1,796 | $ - | $ 1,796 | | 2 x 6,500 gal holding tank (rental) |
| months | 2 | $ 8,000.00 | $ - | $ 16,000 | $ - | $ 16,000 | | UF membrane unit for CD reconcentration (rental) |
| EA | 1 | $ - | $ 16,979 | $ - | $ 16,979 | $ 16,979 | | 4000 lbs air activated carbon filter system (rental) |
| months | 4 | $ 832.00 | $ - | $ 3,328 | $ - | $ 3,328 | | Suspended solid filter system (rental) |
| EA | 1 | | $ 368.00 | $ - | $ 368 | $ 368 | | 250 gal mixing tank (purchase) |
| months | 4 | $ 54.00 | $ - | $ 216 | $ - | $ 216 | | On-site sanitation (rental) |
| months | 2 | $ 1,497.00 | $ - | $ 2,994 | $ - | $ 2,994 | | Diesel electric generator (480 V, 30KW) (rental) |
| | | | | | | | **$ 51,782** | **Total Equipment Ownership and Rental Cost** |

**Performance Testing and Analysis**

***Analysis Cost - off-site***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 120 | $ 124.00 | $ - | $ 14,880 | $ - | $ 14,880 | | VOC analysis |
| | | | | | | | **$ 14,880** | **Total Performance Testing and Analysis - off site** |

***Analysis Cost - on-site***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 120 | $ 25.00 | $ - | $ 3,000 | $ - | $ 3,000 | | CD analysis (TOC method) |
| EA | 120 | $ 50.00 | $ - | $ 6,000 | $ - | $ 6,000 | | Field parameters (set of pH, DO, T, EC) |
| EA | 1 | $ - | $ 1,000 | $ - | $ 1,000 | $ 1,000 | | Miscellaneous field lab supplies |
| | | | | | | | **$ 1,000** | **Total Performance Testing and Analysis - on site** |

**Other (non-process related)**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| hrs | 160 | $ 125 | $ - | $ 20,000 | $ - | $ 20,000 | | Final report preparation (PI) |
| EA | 1 | $ - | $ 4,496 | $ - | $ 4,496 | $ 4,496 | | PID for H&S survey, personal protective equip. |
| EA | 60 | $ - | $ 25 | $ - | $ 1,500 | $ 1,500 | | S/H of samples |
| | | | | | | | **$ 25,996** | Total Other (non-process related) |
| | | | | | | | **$ 184,532** | **Total Direct Capital** |
| | | | | | | | $ 43,408 | Overhead and Administration |
| | | | | | | | $ - | Contingency |
| | | | | | | | **$ 43,408** | **Total Indirect Operational** |
| | | | | | | | **$ 227,940** | **TOTAL OPERATIONAL** |

## OTHER TECHNOLGOY SPECIFIC COSTS (real-world cost)

**Compliance Testing and Analysis**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 8 | $ - | $ 124.00 | $ - | $ 992 | $ 992 | | Compliance sampling |
| | | | | | | | $ 992 | **Total Compliance Testing and Analysis** |

**Disposal of Hazardeous Waste**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 3,900 | $ - | $ 3,900 | $ 3,900 | | | Off-site disposal of drill cuttings |
| | | | | | | | $ 3,900 | | **Total Disposal of Hazardeous Waste (in-kind)** |

| | |
|---|---|
| $ 4,892 | **Total Direct Other Technol. Specific Cost** |
| $ 1,433 | Overhead and Administration |
| $ - | Contingency |
| $ 1,433 | **Total Indirect Other Technol. Specific Cost** |
| $ 6,325 | **TOTAL OTHER TECHNOL. SPECIFIC COSTS** |

## OTHER PROJECT COSTS (real-world cost)

**Site Restoration**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 8 | $ 50.00 | $ - | $ 400 | $ - | $ 400 | | Site restoration (landscaping) |
| | | | | | | | $ 400 | **Total Site Restoration** |

| | |
|---|---|
| $ 400 | **Total Direct Other ProjectCost** |
| $ 117 | Overhead and Administration |
| $ - | Contingency |
| $ 117 | **Total Indirect Other Project Cost** |
| $ 517 | **TOTAL OTHER TECHNOL. SPECIFIC COSTS** |

## COST SUMMARY (real-world cost)

| | |
|---|---|
| $ 395,440 | **Total Cost (demonstration)** |

**Unit Cost - Quantity of Contaminant Removed and Treated**

| | |
|---|---|
| 25.8 | **Quantity of Media Removed and Treated (lbs VOC)** |
| $ 15,327.12 | **Calculated Unit Cost ($/lbs)** |
| VOC removed | **Basis for Quantity Treated** |

**Unit Cost - Quantity of Groundwater Treated**

| | |
|---|---|
| 837270.0 | **Quantity of Media Removed and Treated (gal groundwater)** |
| $ 0.47 | **Calculated Unit Cost ($/gal)** |
| GW treated | **Basis for Quantity Treated** |

**Unit Cost - Quantity of Soil Treated**

| | |
|---|---|
| 49.3 | **Quantity of Media Removed and Treated** |
| $ 8,021.09 | **Calculated Unit Cost ($/ton)** |
| Soil treated | **Basis for Quantity Treated** |

# Appendix VIII:
## Simulation of Required CD mass and Remediation Duration
## - Large Scale 2,500 $ft^2$ -

**Simulation of CDEF Remediation**

Shaded cells mark variables

| | | | |
|---|---|---|---|
| **Contaminant:** | **VOC (TCE+1,1,1-TCA+1,1-DCE)** | | |
| **Treatment approach:** | **Multi-Well Push-Pull (CPPT) with UF in batch operati** | | |
| **1.a Extent of contaminated area:** | | | |
| Width | **15.3** | m | |
| Length | **15.3** | m | |
| Vertical extent | **1.5** | m | |
| Area treated | 234 | m2 | |
| $Vol_{soil}$ | 351 | m3 | |
| Soil weight based on bulk density = 1.7 t/m3 | 597 | tons (soil density = 1.7 t/m3) | |
| $rho_{contaminant}$ (Density) | **1400** | kg/m3 | |
| n (Porosity) | **0.31** | | |
| $F_{removal}$ NAPL mass removal per m3 flushed | **0.139** | kg | |
| PV (vol of injected CD slug) | **108.9** | m3 | |
| Injection Conc $_{HPCD}$ | **20** | % | 200 kg/m3 |
| Cost $_{HPCD}$ | **4.50** | $/kg | |
| R (Efficiency of contamiant removal) | **90** | % | |
| $CD_{recovery}$ from treatment zone | **97** | % | |
| Q (Pumping rate) (injection rate = extraction rate) | **32.6** | m3/d | 6.0 gpm |
| For CPPT only: ratio injection/extraction time | **0.67** | | |
| For CPPT only: extracted vol. per CPPT | 72.9 | m3 | |
| **1. b: Degree of contamination - Contaminant mass** | | | |
| $m_{initial}$ | **643** | kg | 459.5 liter |
| $m_{90\%}$ | **579** | kg | 413.5 liter |
| Avg. Contaminant concentration in solid matrix | 970 | $mg_{cont}/kg_{soil}$ | |
| **1. c: Treatment rate** | | | |
| Slug size per well (CPPT) | 2.7 | m3 | |
| Injection/extraction rate (CPPT) per well | 8 | m3/day | 1.5 gpm |
| Number of wells needed to treat one PV | 40 | wells | |
| Time needed to inject and extract flushing solution (CPPT) | 0.34 | days | 8.1 hours |
| UF treatment capacity | 32.6 | m3/day | 6.0 gpm |
| Time necessary to recycle one PV flushing solution using UF | 3.3 | days | |
| **2. Calculate theoretical mass and volume of CD required to remove 90% NAPL** | | | |
| VOC mass removed per kg CD | 0.0021 | kg | |
| Mass of CD necessary to remove 90% NAPL W/O recycling | 276 | tons | |
| Vol. of 20% CD solution to remove 90% NAPL | 1378 | m3 | |
| **3. Calculate number of total PV's necessary to remove contaminant** | | | |
| $PV_{flushed} = m_{90\%} / F_{removal} / PV$ | 38.3 | PV | |
| Uncertainty factor of : | **1.25** | | |
| Actual number of PV needed: | 47.8 | PV | |
| **4. Calculate total mass of CD needed to remove contaminant** | | | |
| 4.a) CD mass applied per PV = Conc $_{CD}$ x $m^3$/PV = | 21770 | kg | |
| 4.b) CD mass added to make-up for incomplete mass recovery from subsurface =CD mass per PV - (CD mass per PV x CD $_{recovery}$) | 653 | kg | |
| 4.c) CD mass recoverd by UF | 19006 | kg | |
| assume: | **90%** | UF recovery efficiency | |
| 4.d) Total CD mass needed to recondition flushing solution to 20% per PV | 3418 | kg | |
| **4.e) Total mass of CD needed to achieve 90% removal** | **185.2** | **tons** | |
| **4.f) Total cost CD** | **$833,613** | | |
| **4. g) Material cost savings due to CD reuse** | **$3,852,032** | | |
| **5. Remediaiton time estimate for 90% mass removal** | | | |
| No. of CPPT application per week: | 2.1 | | |
| **Estimated duration to achieve end-point** | **5.7** | **months** | |

**Simulation of CDEF Remediation**

Shaded cells mark variables

| | | | |
|---|---|---|---|
| **Contaminant:** | **VOC (TCE+1,1,1-TCA+1,1-DCE)** | | |
| **Treatment approach:** | **Multi-Well Push-Pull (CPPT) with UF in continuous operation** | | |
| **1.a Extent of contaminated area:** | | | |
| Width | **15.3** | m | |
| Length | **15.3** | m | |
| Vertical extent | **1.5** | m | |
| Area treated | 234 | m2 | |
| $Vol_{soil}$ | 351 | m3 | |
| Soil weight based on bulk density = 1.7 t/m3 | 597 | tons (soil density = 1.7 t/m3) | |
| $rho_{contaminant}$ (Density) | **1400** | kg/m3 | |
| n (Porosity) | **0.31** | | |
| $F_{removal}$ NAPL mass removal per m3 flushed | **0.139** | kg | |
| PV (vol of injected CD slug) | **108.9** | m3 | |
| Injection Conc $_{HPCD}$ | **20** | % | 200 kg/m3 |
| Cost $_{HPCD}$ | **4.50** | \$/kg | |
| R (Efficiency of contamiant removal) | **90** | % | |
| $CD_{recovery}$ from treatment zone | **97** | % | |
| Q (Pumping rate) (injection rate = extraction rate) | **32.6** | m3/d | 6.0 gpm |
| For CPPT only: ratio injection/extraction time | **0.67** | | |
| For CPPT only: extracted vol. per CPPT | 72.9 | m3 | |
| **1. b: Degree of contamination - Contaminant mass** | | | |
| $m_{initial}$ | **643** | kg | 459.5 liter |
| $m_{90\%}$ | **579** | kg | 413.5 liter |
| Avg. Contaminant concentration in solid matrix | 970 | $mg_{cont}/kg_{soil}$ | |
| **1. c: Treatment rate** | | | |
| Slug size per well (CPPT) | 2.7 | m3 | |
| Injection/extraction rate (CPPT) per well | 8 | m3/day | 1.5 gpm |
| Number of wells needed to treat one PV | 40 | wells | |
| Time needed to inject and extract flushing solution (CPPT) | 0.34 | days | 8.1 hours |
| UF treatment capacity | 32.6 | m3/day | 6.0 gpm |
| Time necessary to recycle one PV flushing solution using UF | 3.3 | days | |
| **2. Calculate theoretical mass and volume of CD required to remove 90% NAPL** | | | |
| VOC mass removed per kg CD | 0.0021 | kg | |
| Mass of CD necessary to remove 90% NAPL W/O recycling | 276 | tons | |
| Vol. of 20% CD solution to remove 90% NAPL | 1378 | m3 | |
| **3. Calculate number of total PV's necessary to remove contaminant** | | | |
| $PV_{flushed} = m_{90\%} / F_{removal} / PV$ | 38.3 | PV | |
| Uncertainty factor of : | **1.25** | | |
| Actual number of PV needed: | 47.8 | PV | |
| **4. Calculate total mass of CD needed to remove contaminant** | | | |
| 4.a) CD mass applied per PV = Conc $_{CD}$ x $m^3$/PV = | 21770 | kg | |
| 4.b) CD mass added to make-up for incomplete mass recovery from subsurface =CD mass per PV - (CD mass per PV x CD $_{recovery}$) | 653 | kg | |
| 4.c) CD mass recoverd by UF | 14360 | kg | |
| assume: | **68%** | UF recovery efficiency | |
| 4.d) Total CD mass needed to recondition flushing solution to 20% per PV | 8064 | kg | |
| **4.e) Total mass of CD needed to achieve 90% removal** | **407.5** | **tons** | |
| **4.f) Total cost CD** | **\$1,833,530** | | |
| **4. g) Material cost savings due to CD reuse** | **\$2,852,115** | | |
| **5. Remediaiton time estimate for 90% mass removal** | | | |
| No. of CPPT application per week: | 6.0 | | |
| **Estimated duration to achieve end-point** | **2.0** | **months** | |

**Simulation of CDEF Remediation**

Shaded cells mark variables

| | | | |
|---|---|---|---|
| **Contaminant:** | **VOC (TCE+1,1,1-TCA+1,1-DCE)** | | |
| **Treatment approach:** | **Multi-Well Push-Pull (CPPT) with no UF** | | |
| **1.a Extent of contaminated area:** | | | |
| Width | **15.3** | m | |
| Length | **15.3** | m | |
| Vertical extent | **1.5** | m | |
| Area treated | 234 | m2 | |
| $Vol_{soil}$ | 351 | m3 | |
| Soil weight based on bulk density = 1.7 t/m3 | 597 | tons (soil density = 1.7 t/m3) | |
| $rho_{contaminant}$ (Density) | **1400** | kg/m3 | |
| n (Porosity) | **0.31** | | |
| $F_{removal}$ NAPL mass removal per m3 flushed | **0.139** | kg | |
| PV (vol of injected CD slug) | **108.9** | m3 | |
| Injection Conc $_{HPCD}$ | **20** | % | 200 kg/m3 |
| Cost $_{HPCD}$ | **4.50** | $/kg | |
| R (Efficiency of contamiant removal) | **90** | % | |
| $CD_{recovery}$ from treatment zone | **97** | % | |
| Q (Pumping rate) (injection rate = extraction rate) | **32.6** | m3/d | 6.0 gpm |
| For CPPT only: ratio injection/extraction time | **0.67** | | |
| For CPPT only: extracted vol. per CPPT | 72.9 | m3 | |
| **1. b: Degree of contamination - Contaminant mass** | | | |
| $m_{initial}$ | **643** | kg | 459.5 liter |
| $m_{90\%}$ | **579** | kg | 413.5 liter |
| Avg. Contaminant concentration in solid matrix | 970 | $mg_{cont}/kg_{soil}$ | |
| **1. c: Treatment rate** | | | |
| Slug size per well (CPPT) | 2.7 | m3 | |
| Injection/extraction rate (CPPT) per well | 8 | m3/day | 1.5 gpm |
| Number of wells needed to treat one PV | 40 | wells | |
| Time needed to inject and extract flushing solution (CPPT) | 0.34 | days | 8.1 hours |
| UF treatment capacity | 32.6 | m3/day | 6.0 gpm |
| Time necessary to recycle one PV flushing solution using UF | 3.3 | days | |
| **2. Calculate theoretical mass and volume of CD required to remove 90% NAPL** | | | |
| VOC mass removed per kg CD | 0.0021 | kg | |
| Mass of CD necessary to remove 90% NAPL W/O recycling | 276 | tons | |
| Vol. of 20% CD solution to remove 90% NAPL | 1378 | m3 | |
| **3. Calculate number of total PV's necessary to remove contaminant** | | | |
| $PV_{flushed} = m_{90\%} / F_{removal} / PV$ | 38.3 | PV | |
| Uncertainty factor of : | **1.25** | | |
| Actual number of PV needed: | 47.8 | PV | |
| **4. Calculate total mass of CD needed to remove contaminant** | | | |
| 4.a) CD mass applied per PV = Conc $_{CD}$ x $m^3$/PV = | 21770 | kg | |
| 4.b) CD mass added to make-up for incomplete mass recovery from subsurface =CD mass per PV - (CD mass per PV x CD $_{recovery}$) | 653 | kg | |
| 4.c) CD mass recoverd by UF | 0 | kg | |
| assume: | **0%** | UF recovery efficiency | |
| 4.d) Total CD mass needed to recondition flushing solution to 20% per PV | 22423 | kg | |
| **4.e) Total mass of CD needed to achieve 90% removal** | **1094.3** | **tons** | |
| **4.f) Total cost CD** | **$4,924,181** | | |
| **4. g) Material cost savings due to CD reuse** | **$0** | | |
| **5. Remediaiton time estimate for 90% mass removal** | | | |
| No. of CPPT application per week: | 6.0 | | |
| **Estimated duration to achieve end-point** | **2.0** | **months** | |

## Simulation of CDEF Remediation

Shaded cells mark variables

| | | | |
|---|---|---|---|
| **Contaminant:** | **VOC (TCE+1,1,1-TCA+1,1-DCE)** | | |
| **Treatment approach:** | **Line drive (I/E) with UF in continuous operation** | | |
| **1.a Extent of contaminated area:** | | | |
| Width | **15.3** | m | |
| Length | **15.3** | m | |
| Vertical extent | **1.5** | m | |
| Area treated | 234 | m2 | |
| $Vol_{soil}$ | 351 | m3 | |
| Soil weight based on bulk density = 1.7 t/m3 | 597 | tons (soil density = 1.7 t/m3) | |
| $rho_{contaminant}$ (Density) | **1400** | kg/m3 | |
| n (Porosity) | **0.31** | | |
| $F_{removal}$ NAPL mass removal per m3 flushed | **0.139** | kg | |
| PV (vol of injected CD slug) | **108.9** | m3 | |
| Injection Conc $_{HPCD}$ | **20** | % | 200 kg/m3 |
| Cost $_{HPCD}$ | **4.50** | \$/kg | |
| R (Efficiency of contamiant removal) | **90** | % | |
| $CD_{recovery}$ from treatment zone | **79** | % | |
| Q (Pumping rate) (injection rate = extraction rate) | **32.6** | m3/d | 6.0 gpm |
| For CPPT only: ratio injection/extraction time | **0.67** | | |
| For CPPT only: extracted vol. per CPPT | 72.9 | m3 | |
| **1. b: Degree of contamination - Contaminant mass** | | | |
| $m_{initial}$ | **643** | kg | 459.5 liter |
| $m_{90\%}$ | **579** | kg | 413.5 liter |
| Avg. Contaminant concentration in solid matrix | 970 | $mg_{cont}/kg_{soil}$ | |
| **1. c: Treatment rate** | | | |
| Time needed to treat 1 PV | 11.6 | days | |
| Number of injection wells | 14 | wells | |
| Number of extraction wells | 24 | wells | |
| Number of hydraulic control wells | 8 | wells | |
| Total number of injection and extraction wells | 38 | wells | |
| UF treatment capacity | 8 | m3/day | 1.5 gpm |
| Time necessary to recycle one PV flushing solution using UF | 13.6 | days | |
| **2. Calculate theoretical mass and volume of CD required to remove 90% NAPL** | | | |
| VOC mass removed per kg CD | 0.0016 | kg | |
| Theor. mss of CD necessary to remove 90% NAPL W/O recycling | 362 | tons | |
| Vol. of 20% CD solution to remove 90% NAPL | 1809 | m3 | |
| **3. Calculate number of total PV's necessary to remove contaminant** | | | |
| $PV_{flushed} = m_{90\%} / F_{removal} / PV$ | 38.3 | PV | |
| Uncertainty factor of : | **1.25** | | |
| Actual number of PV needed: | 47.8 | PV | |
| **4. Calculate total mass of CD needed to remove contaminant** | | | |
| 4.a) CD mass applied per PV = Conc $_{CD}$ x $m^3$/PV = | 21770 | kg | |
| 4.b) CD mass added to make-up for incomplete mass recovery from subsurface =CD mass per PV - (CD mass per PV x CD $_{recovery}$) | 4572 | kg | |
| 4.c) CD mass recoverd by UF | 11695 | kg | |
| assume: | **68%** | UF recovery efficiency | |
| 4.d) Total CD mass needed to recondition flushing solution to 20% per PV | 14647 | kg | |
| **4.e) Total mass of CD needed to achieve 90% removal** | **722.3** | **tons** | |
| **4.f) Total cost CD** | **\$3,250,469** | | |
| **4. g) Material cost savings due to CD reuse** | **\$1,435,176** | | |
| **5. Remediaiton time estimate for 90% mass removal** | | | |
| **Estimated duration to achieve end-point** | **18.5** | **months** | |

**Simulation of CDEF Remediation**

Shaded cells mark variables

| | | | |
|---|---|---|---|
| **Contaminant:** | **VOC (TCE+1,1,1-TCA+1,1-DCE)** | | |
| **Treatment approach:** | **Line-Drive (I/E) with no UF** | | |

**1.a Extent of contaminated area:**

| | | | |
|---|---|---|---|
| Width | **15.3** | m | |
| Length | **15.3** | m | |
| Vertical extent | **1.5** | m | |
| Area treated | 234 | m2 | |
| $Vol_{soil}$ | 351 | m3 | |
| Soil weight based on bulk density = 1.7 t/m3 | 597 | tons (soil density = 1.7 t/m3) | |
| $rho_{contaminant}$ (Density) | **1400** | kg/m3 | |
| n (Porosity) | **0.31** | | |
| $F_{removal}$ NAPL mass removal per m3 flushed | **0.139** | kg | |
| PV (vol of injected CD slug) | **108.9** | m3 | |
| Injection Conc $_{HPCD}$ | **20** | % | 200 kg/m3 |
| Cost $_{HPCD}$ | **4.50** | $/kg | |
| R (Efficiency of contamiant removal) | **90** | % | |
| $CD_{recovery}$ from treatment zone | **79** | % | |
| Q (Pumping rate) (injection rate = extraction rate) | **32.6** | m3/d | 6.0 gpm |
| For CPPT only: ratio injection/extraction time | **0.67** | | |
| For CPPT only: extracted vol. per CPPT | 72.9 | m3 | |

**1. b: Degree of contamination - Contaminant mass**

| | | | |
|---|---|---|---|
| $m_{initial}$ | **643** | kg | 459.5 liter |
| $m_{90\%}$ | **579** | kg | 413.5 liter |
| Avg. Contaminant concentration in solid matrix | 970 | $mg_{cont}/kg_{soil}$ | |

**1. c: Treatment rate**

| | | | |
|---|---|---|---|
| Time needed to treat 1 PV | 11.6 | days | |
| Number of injection wells | 14 | wells | |
| Number of extraction wells | 24 | wells | |
| Number of hydraulic control wells | 8 | wells | |
| Total number of injection and extraction wells | 38 | wells | |
| UF treatment capacity | 8 | m3/day | 1.5 gpm |
| Time necessary to recycle one PV flushing solution using UF | 13.6 | days | |

**2. Calculate theoretical mass and volume of CD required to remove 90% NAPL**

| | | |
|---|---|---|
| VOC mass removed per kg CD | 0.0016 | kg |
| Theor. mss of CD necessary to remove 90% NAPL W/O recycling | 362 | tons |
| Vol. of 20% CD solution to remove 90% NAPL | 1809 | m3 |

**3. Calculate number of total PV's necessary to remove contaminant**

| | | |
|---|---|---|
| $PV_{flushed} = m_{90\%} / F_{removal} / PV$ | 38.3 | PV |
| Uncertainty factor of : | **1.25** | |
| Actual number of PV needed: | 47.8 | PV |

**4. Calculate total mass of CD needed to remove contaminant**

| | | |
|---|---|---|
| 4.a) CD mass applied per PV = Conc $_{CD}$ x $m^3$/PV = | 21770 | kg |
| 4.b) CD mass added to make-up for incomplete mass recovery from subsurface =CD mass per PV - (CD mass per PV x CD $_{recovery}$) | 4572 | kg |
| 4.c) CD mass recoverd by UF | 0 | kg |
| assume: | **0%** | UF recovery efficiency |
| 4.d) Total CD mass needed to recondition flushing solution to 20% per PV | 26342 | kg |
| **4.e) Total mass of CD needed to achieve 90% removal** | **1281.7** | **tons** |
| **4.f) Total cost CD** | **$5,767,597** | |
| **4. g) Material cost savings due to CD reuse** | **$0** | |

**5. Remediaiton time estimate for 90% mass removal**

| | | |
|---|---|---|
| **Estimated duration to achieve end-point** | **18.5** | **months** |

## o Small Scale 300 $ft^2$ –

**Simulation of CDEF Remediation**

Shaded cells mark variables

| | | | |
|---|---|---|---|
| **Contaminant:** | **VOC (TCE+1,1,1-TCA+1,1-DCE)** | | |
| **Treatment approach:** | **Multi-Well Push-Pull (CPPT) with UF in batch operation** | | |
| **1.a Extent of contaminated area:** | | | |
| Width | **4.4** | m | |
| Length | **4.4** | m | |
| Vertical extent | **1.5** | m | |
| Area treated | 19 | m2 | |
| $Vol_{soil}$ | 29 | m3 | |
| Soil weight based on bulk density = 1.7 t/m3 | 49 | tons (soil density = 1.7 t/m3) | |
| $rho_{contaminant}$ (Density) | **1400** | kg/m3 | |
| n (Porosity) | **0.31** | | |
| $F_{removal}$ NAPL mass removal per m3 flushed | **0.139** | kg | |
| PV (vol of injected CD slug) | **9.0** | m3 | |
| Injection Conc $_{HPCD}$ | **20** | % | 200 kg/m3 |
| Cost $_{HPCD}$ | **4.50** | $/kg | |
| R (Efficiency of contamiant removal) | **90** | % | |
| $CD_{recovery}$ from treatment zone | **97** | % | |
| Q (Pumping rate) (injection rate = extraction rate) | **18.5** | m3/d | 3.4 gpm |
| For CPPT only: ratio injection/extraction time | **0.67** | | |
| **1. b: Degree of contamination - Contaminant mass** | | | |
| $m_{initial}$ | **53** | kg | 38.0 liter |
| $m_{90\%}$ | **48** | kg | 34.2 liter |
| Avg. Contaminant concentration in solid matrix | 970 | $mg_{cont}/kg_{soil}$ | |
| **1. c: Treatment rate** | | | |
| Number of wells needed to treat one PV | **6** | wells | |
| Slug size per well (CPPT) | 1.5 | m3 | |
| Injection/extraction rate (CPPT) per well | **5.5** | m3/day | 1.0 gpm |
| UF treatment capacity | **9.0** | m3/day | 1.7 gpm |
| Time necessary to recycle one PV flushing solution using UF | 1.0 | days | |
| **2. Calculate theoretical mass and volume of CD required to remove 90% NAPL** | | | |
| VOC mass removed per kg CD | 0.0021 | kg | |
| Mass of CD necessary to remove 90% NAPL W/O recycling | 23 | tons | |
| Vol. of 20% CD solution to remove 90% NAPL | 114 | m3 | |
| **3. Calculate number of total PV's necessary to remove contaminant** | | | |
| $PV_{flushed} = m_{90\%} / F_{removal} / PV$ | 38.3 | PV | |
| Uncertainty factor of : | **1.25** | | |
| Actual number of PV needed: | 47.8 | PV | |
| **4. Calculate total mass of CD needed to remove contaminant** | | | |
| 4.a) CD mass applied per PV = Conc $_{CD}$ x $m^3$/PV = | 1800 | kg | |
| 4.b) CD mass added to make-up for incomplete mass recovery from subsurface =CD mass per PV - (CD mass per PV x CD $_{recovery}$) | 54 | kg | |
| 4.c) CD mass recoverd by UF | 1572 | kg | |
| assume: | **90%** | UF recovery efficiency | |
| 4.d) Total CD mass needed to recondition flushing solution to 20% per PV | 283 | kg | |
| **4.e) Total mass of CD needed to achieve 90% removal** | **15.3** | **tons** | |
| **4.f) Total cost CD** | **$68,942** | | |
| **4. g) Material cost savings due to CD reuse** | **$318,576** | | |
| **5. Remediaiton time estimate for 90% mass removal** | | | |
| No. of CPPT application per week: | 3.0 | | |
| **Estimated duration to achieve end-point** | **4.0** | **months** | |

## Simulation of CDEF Remediation

Shaded cells mark variables

| | | | |
|---|---|---|---|
| **Contaminant:** | **VOC (TCE+1,1,1-TCA+1,1-DCE)** | | |
| **Treatment approach:** | **Multi-Well Push-Pull (CPPT) with UF in continuous operation** | | |
| **1.a Extent of contaminated area:** | | | |
| Width | **4.4** | m | |
| Length | **4.4** | m | |
| Vertical extent | **1.5** | m | |
| Area treated | 19 | m2 | |
| $Vol_{soil}$ | 29 | m3 | |
| Soil weight based on bulk density = 1.7 t/m3 | 49 | tons (soil density = 1.7 t/m3) | |
| $rho_{contaminant}$ (Density) | **1400** | kg/m3 | |
| n (Porosity) | **0.31** | | |
| $F_{removal}$ NAPL mass removal per m3 flushed | **0.139** | kg | |
| PV (vol of injected CD slug) | **9.0** | m3 | |
| Injection Conc $_{HPCD}$ | **20** | % | 200 kg/m3 |
| Cost $_{HPCD}$ | **4.50** | $/kg | |
| R (Efficiency of contamiant removal) | **90** | % | |
| $CD_{recovery}$ from treatment zone | **97** | % | |
| Q (Pumping rate) (injection rate = extraction rate) | **32.6** | m3/d | 6.0 gpm |
| For CPPT only: ratio injection/extraction time | **0.67** | | |
| **1. b: Degree of contamination - Contaminant mass** | | | |
| $m_{initial}$ | **53** | kg | 38.0 liter |
| $m_{90\%}$ | **48** | kg | 34.2 liter |
| Avg. Contaminant concentration in solid matrix | 970 | $mg_{cont}/kg_{soil}$ | |
| **1. c: Treatment rate** | | | |
| Number of wells needed to treat one PV | **6** | wells | |
| Slug size per well (CPPT) | 1.5 | m3 | |
| Injection/extraction rate (CPPT) per well | **5.5** | m3/day | 1.0 gpm |
| UF treatment capacity | **9.0** | m3/day | 1.7 gpm |
| Time necessary to recycle one PV flushing solution using UF | 1.0 | days | |
| **2. Calculate theoretical mass and volume of CD required to remove 90% NAPL** | | | |
| VOC mass removed per kg CD | 0.0021 | kg | |
| Mass of CD necessary to remove 90% NAPL W/O recycling | 23 | tons | |
| Vol. of 20% CD solution to remove 90% NAPL | 114 | m3 | |
| **3. Calculate number of total PV's necessary to remove contaminant** | | | |
| $PV_{flushed} = m_{90\%} / F_{removal}$ / PV | 38.3 | PV | |
| Uncertainty factor of : | **1.25** | | |
| Actual number of PV needed: | 47.8 | PV | |
| **4. Calculate total mass of CD needed to remove contaminant** | | | |
| 4.a) CD mass applied per PV = Conc $_{CD}$ x $m^3$/PV = | 1800 | kg | |
| 4.b) CD mass added to make-up for incomplete mass recovery from subsurface =CD mass per PV - (CD mass per PV x CD $_{recovery}$) | 54 | kg | |
| 4.c) CD mass recoverd by UF | 1188 | kg | |
| assume: | **68%** | UF recovery efficiency | |
| 4.d) Total CD mass needed to recondition flushing solution to 20% per PV | 667 | kg | |
| **4.e) Total mass of CD needed to achieve 90% removal** | **33.7** | **tons** | |
| **4.f) Total cost CD** | **$151,639** | | |
| **4. g) Material cost savings due to CD reuse** | **$235,879** | | |
| **5. Remediaiton time estimate for 90% mass removal** | | | |
| No. of CPPT application per week: | 6.0 | | |
| **Estimated duration to achieve end-point** | **2.0** | **months** | |

**Simulation of CDEF Remediation**

Shaded cells mark variables

| | | | |
|---|---|---|---|
| **Contaminant:** | **VOC (TCE+1,1,1-TCA+1,1-DCE)** | | |
| **Treatment approach:** | **Multi-Well Push-Pull (CPPT) with no UF** | | |
| **1.a Extent of contaminated area:** | | | |
| Width | **4.4** | m | |
| Length | **4.4** | m | |
| Vertical extent | **1.5** | m | |
| Area treated | 19 | m2 | |
| $Vol_{soil}$ | 29 | m3 | |
| Soil weight based on bulk density = 1.7 t/m3 | 49 | tons (soil density = 1.7 t/m3) | |
| $rho_{contaminant}$ (Density) | **1400** | kg/m3 | |
| n (Porosity) | **0.31** | | |
| $F_{removal}$ NAPL mass removal per m3 flushed | **0.139** | kg | |
| PV (vol of injected CD slug) | **9.0** | m3 | |
| Injection Conc $_{HPCD}$ | **20** | % | 200 kg/m3 |
| Cost $_{HPCD}$ | **4.50** | \$/kg | |
| R (Efficiency of contamiant removal) | **90** | % | |
| $CD_{recovery}$ from treatment zone | **97** | % | |
| Q (Pumping rate) (injection rate = extraction rate) | **32.6** | m3/d | 6.0 gpm |
| For CPPT only: ratio injection/extraction time | **0.67** | | |
| **1. b: Degree of contamination - Contaminant mass** | | | |
| $m_{initial}$ | **53** | kg | 38.0 liter |
| $m_{90\%}$ | **48** | kg | 34.2 liter |
| Avg. Contaminant concentration in solid matrix | 970 | $mg_{cont}/kg_{soil}$ | |
| **1. c: Treatment rate** | | | |
| Number of wells needed to treat one PV | **6** | wells | |
| Slug size per well (CPPT) | 1.5 | m3 | |
| Injection/extraction rate (CPPT) per well | **5.5** | m3/day | 1.0 gpm |
| UF treatment capacity | **9.0** | m3/day | 1.7 gpm |
| Time necessary to recycle one PV flushing solution using UF | 1.0 | days | |
| **2. Calculate theoretical mass and volume of CD required to remove 90% NAPL** | | | |
| VOC mass removed per kg CD | 0.0021 | kg | |
| Mass of CD necessary to remove 90% NAPL W/O recycling | 23 | tons | |
| Vol. of 20% CD solution to remove 90% NAPL | 114 | m3 | |
| **3. Calculate number of total PV's necessary to remove contaminant** | | | |
| $PV_{flushed} = m_{90\%} / F_{removal} / PV$ | 38.3 | PV | |
| Uncertainty factor of : | **1.25** | | |
| Actual number of PV needed: | 47.8 | PV | |
| **4. Calculate total mass of CD needed to remove contaminant** | | | |
| 4.a) CD mass applied per PV = Conc $_{CD}$ x $m^3$/PV = | 1800 | kg | |
| 4.b) CD mass added to make-up for incomplete mass recovery from subsurface =CD mass per PV - (CD mass per PV x CD $_{recovery}$) | 54 | kg | |
| 4.c) CD mass recoverd by UF | 0 | kg | |
| assume: | **0%** | UF recovery efficiency | |
| 4.d) Total CD mass needed to recondition flushing solution to 20% per PV | 1854 | kg | |
| **4.e) Total mass of CD needed to achieve 90% removal** | **90.5** | **tons** | |
| **4.f) Total cost CD** | **\$407,246** | | |
| **4. g) Material cost savings due to CD reuse** | **\$0** | | |
| **5. Remediaiton time estimate for 90% mass removal** | | | |
| No. of CPPT application per week: | 6.0 | | |
| **Estimated duration to achieve end-point** | **2.0** | **months** | |

## Simulation of CDEF Remediation

Shaded cells mark variables

| | | |
|---|---|---|
| **Contaminant:** | **VOC (TCE+1,1,1-TCA+1,1-DCE)** | |
| **Treatment approach:** | **Line drive (I/E) with UF in continuous operation** | |
| **1.a Extent of contaminated area:** | | |
| Width | **4.4** m | |
| Length | **4.4** m | |
| Vertical extent | **1.5** m | |
| Area treated | 19 m2 | |
| $Vol_{soil}$ | 29 m3 | |
| Soil weight based on bulk density = 1.7 t/m3 | 49 tons (soil density = 1.7 t/m3) | |
| $rho_{contaminant}$ (Density) | **1400** kg/m3 | |
| n (Porosity) | **0.31** | |
| $F_{removal}$ NAPL mass removal per m3 flushed | **0.139** kg | |
| PV (vol of injected CD slug) | **9.0** m3 | |
| Injection Conc $_{HPCD}$ | **20** % | 200 kg/m3 |
| Cost $_{HPCD}$ | **4.50** $/kg | |
| R (Efficiency of contamiant removal) | **90** % | |
| $CD_{recovery}$ from treatment zone | **79** % | |
| Q (Pumping rate) (injection rate = extraction rate) | **32.6** m3/d | 6.0 gpm |
| **1. b: Degree of contamination - Contaminant mass** | | |
| $m_{initial}$ | **53** kg | 38.0 liter |
| $m_{90\%}$ | **48** kg | 34.2 liter |
| Avg. Contaminant concentration in solid matrix | 970 $mg_{cont}/kg_{soil}$ | |
| **1. c: Treatment rate** | | |
| Time needed to treat 1 PV | **1.0** days | |
| Number of injection wells | 3 wells | |
| Number of extraction wells | 3 wells | |
| Number of hydraulic control wells | 2 wells | |
| UF treatment capacity | 9.0 m3/day | 1.7 gpm |
| Time necessary to recycle one PV flushing solution using UF | 1.0 days | |
| **2. Calculate theoretical mass and volume of CD required to remove 90% NAPL** | | |
| VOC mass removed per kg CD | 0.0016 kg | |
| Theor. mss of CD necessary to remove 90% NAPL W/O recycling | 30 tons | |
| Vol. of 20% CD solution to remove 90% NAPL | 150 m3 | |
| **3. Calculate number of total PV's necessary to remove contaminant** | | |
| $PV_{flushed} = m_{90\%} / F_{removal} / PV$ | 38.3 PV | |
| Uncertainty factor of : | **1.25** | |
| Actual number of PV needed: | 47.8 PV | |
| **4. Calculate total mass of CD needed to remove contaminant** | | |
| 4.a) CD mass applied per PV = Conc $_{CD}$ x $m^3$/PV = | 1800 kg | |
| 4.b) CD mass added to make-up for incomplete mass recovery from subsurface =CD mass per PV - (CD mass per PV x CD $_{recovery}$) | 378 kg | |
| 4.c) CD mass recoverd by UF | 967 kg | |
| assume: | **68%** UF recovery efficiency | |
| 4.d) Total CD mass needed to recondition flushing solution to 20% per PV | 1211 kg | |
| **4.e) Total mass of CD needed to achieve 90% removal** | **59.7 tons** | |
| **4.f) Total cost CD** | **$268,824** | |
| **4. g) Material cost savings due to CD reuse** | **$118,694** | |
| **5. Remediaiton time estimate for 90% mass removal** | | |
| **Estimated duration to achieve end-point** | **1.6 months** | |

**Simulation of CDEF Remediation**

Shaded cells mark variables

| | | | |
|---|---|---|---|
| **Contaminant:** | **VOC (TCE+1,1,1-TCA+1,1-DCE)** | | |
| **Treatment approach:** | **Line-Drive (I/E) with no UF** | | |
| **1.a Extent of contaminated area:** | | | |
| Width | **4.4** | m | |
| Length | **4.4** | m | |
| Vertical extent | **1.5** | m | |
| Area treated | 19 | m2 | |
| $Vol_{soil}$ | 29 | m3 | |
| Soil weight based on bulk density = 1.7 t/m3 | 49 | tons (soil density = 1.7 t/m3) | |
| $rho_{contaminant}$ (Density) | **1400** | kg/m3 | |
| n (Porosity) | **0.31** | | |
| $F_{removal}$ NAPL mass removal per m3 flushed | **0.139** | kg | |
| PV (vol of injected CD slug) | **9.0** | m3 | |
| Injection Conc $_{HPCD}$ | **20** | % | 200 kg/m3 |
| Cost $_{HPCD}$ | **4.50** | $/kg | |
| R (Efficiency of contamiant removal) | **90** | % | |
| $CD_{recovery}$ from treatment zone | **79** | % | |
| Q (Pumping rate) (injection rate = extraction rate) | **32.6** | m3/d | 6.0 gpm |
| **1. b: Degree of contamination - Contaminant mass** | | | |
| $m_{initial}$ | **53** | kg | 38.0 liter |
| $m_{90\%}$ | **48** | kg | 34.2 liter |
| Avg. Contaminant concentration in solid matrix | 970 | $mg_{cont}/kg_{soil}$ | |
| **1. c: Treatment rate** | | | |
| Time needed to treat 1 PV | **1.0** | days | |
| Number of injection wells | 3 | wells | |
| Number of extraction wells | 3 | wells | |
| Number of hydraulic control wells | 2 | wells | |
| UF treatment capacity | 9.0 | m3/day | 1.7 gpm |
| Time necessary to recycle one PV flushing solution using UF | 1.0 | days | |
| **2. Calculate theoretical mass and volume of CD required to remove 90% NAPL** | | | |
| VOC mass removed per kg CD | 0.0016 | kg | |
| Theor. mss of CD necessary to remove 90% NAPL W/O recycling | 30 | tons | |
| Vol. of 20% CD solution to remove 90% NAPL | 150 | m3 | |
| **3. Calculate number of total PV's necessary to remove contaminant** | | | |
| $PV_{flushed} = m_{90\%} / F_{removal} / PV$ | 38.3 | PV | |
| Uncertainty factor of : | **1.25** | | |
| Actual number of PV needed: | 47.8 | PV | |
| **4. Calculate total mass of CD needed to remove contaminant** | | | |
| 4.a) CD mass applied per PV = Conc $_{CD}$ x $m^3$/PV = | 1800 | kg | |
| 4.b) CD mass added to make-up for incomplete mass recovery from subsurface =CD mass per PV - (CD mass per PV x CD $_{recovery}$) | 378 | kg | |
| 4.c) CD mass recoverd by UF | 0 | kg | |
| assume: | **0%** | UF recovery efficiency | |
| 4.d) Total CD mass needed to recondition flushing solution to 20% per PV | 2179 | kg | |
| **4.e) Total mass of CD needed to achieve 90% removal** | **106.0** | **tons** | |
| **4.f) Total cost CD** | **$476,999** | | |
| **4. g) Material cost savings due to CD reuse** | **$0** | | |
| **5. Remediaiton time estimate for 90% mass removal** | | | |
| **Estimated duration to achieve end-point** | **1.6** | **months** | |

# Appendix IX
## Hypothetical Full-Scale Cost System – 2,500 ft$^2$ Scale

**Cyclodextrin Enhanced Flushing at a hypothetical site**

**CAPITAL COST (hypothetical full-scale system)**

**Assumptions**

Treatment approach: **Mulit-well push-pull with UF in batch mode**

| | | | |
|---|---|---|---|
| Flushing Vol: | 109 m3 | Power Cons $ | 0.05725 |
| Soil mass: | 600 tons | Cost / KWH | |
| Area: | 234 m2 | Note: Electrical power for UF is provided by generators. | |
| Project duration: | 6 months | | |

Number of wells, type and depth needed for remediation

40 Injection/extraction wells 22.5 ft

**DNAPL Source Zone Characterization**

Assume: approximate extent of plume is already known

| Units | No of units | Unit labor cost (hr) | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 1,600 | $ - | $ 1,600 | $ 1,600 | | | Mob/Demob Geoprobe/Membrane Interface Probe (MIP) |
| EA | 10 | $ - | $ 3,500 | $ - | $ 35,000 | $ 35,000 | | | MIP with Electrical Conductivity |
| EA | 40 | $ 95 | $ - | $ 3,800 | $ - | $ 3,800 | | | Operator per diem |
| EA | 20 | $ - | $ 1,250 | $ - | $ 25,000 | $ 25,000 | | | In Situ GW/Soil sampling |
| EA | 75 | $ - | $ 126 | $ - | $ 9,450 | $ 9,450 | | | Lab Analysis (TCL Volatile Organic Compound) |
| EA | 480 | $ 50 | $ - | $ 24,000 | $ - | $ 24,000 | | | Labor (2 Person Field Crew) |
| EA | 15 | $ - | $ 200 | $ - | $ 3,000 | $ 3,000 | | | Equipment and Expendables |
| | | | | | | | **$ 101,850** | | **Total DNAPL Source Zone Characterization** |

**Treatability Study (Site soil testing)**

| Units | No of units | Unit labor cost (hr) | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 120 | $ 85 | $ - | $ 10,200 | $ - | $ 10,200 | | | Lab techician (soil column tests) |
| EA | 1 | $ - | $ 2,550 | $ - | $ 2,550 | $ 2,550 | | | Lab equipment |
| EA | 24 | $ 125 | | $ 3,000 | $ - | $ 3,000 | | | Report preparation |
| | | | | | | | **$ 15,750** | | **Total Cyclodextrin Selection** |

**Engineering, Design, and Modeling**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 144 | $ 125 | $ 1,770 | $ 22,000 | $ 1,770 | $ 23,770 | | | Work Plan, H&S plan, Site Management Plan (Project manager) |
| EA | 1 | $ - | $ 12,500 | $ - | $ 12,500 | $ 12,500 | | | Permits and licences, estimated |
| | | | | | | | **$ 36,270** | | **Total Engineering, Design, and Modeling** |

**Technology Mobilization and Demobilizatior**

Assume: Local contractors perform field work

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| hrs | 280 | $ 25 | | $ 7,000 | $ - | $ 7,000 | | | Travel to and from site (incl. accommodation) |
| EA | 2 | $ - | $ 5,464 | $ - | $ 10,928 | $ 10,928 | | | Freight (Palletizing, loading, and shipping of equipmemt) |
| | | | | | | | **$ 17,928** | | **Total Technology Mobilization and Demobilizatior** |

**Site Work**

***Site Set-up***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 1,000 | $ - | $ 1,000 | $ 1,000 | | | Secondary containment (berm) |
| EA | 1 | $ - | $ 1,450 | $ - | $ 1,400 | $ 1,400 | | | Electricity hook-up |
| EA | 540 | $ 30 | $ - | $ 16,200 | $ - | $ 16,200 | | | Plumbing |
| | | | | | | | **$ 18,600** | | **Total Site Set-up** |

**Installation of Equipment and Appurtenances**

***Well Field Installation***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| ft | 900 | $ - | $ 77 | $ - | $ 69,030 | $ 69,030 | | | Injection/Extraction well installation |
| EA | 40 | $ - | $ 552 | $ - | $ 22,080 | $ 22,080 | | | Grunfos submersible pumps (Model 5S) |
| EA | 1 | $ - | $ 14,800 | $ - | $ 14,800 | $ 14,800 | | | SCADA system, automated flow control |
| | | | | | | | **$ 105,910** | | **Total Well Installation** |

***Above Ground Appurtenances***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| ft | 2000 | $ - | $ 2 | $ - | $ 3,600 | $ 3,600 | | | Well piping, 3/4 in PVC and flex tubing |
| EA | 44 | $ - | $ 78 | $ - | $ 3,432 | $ 3,432 | | | Flowmeters |
| EA | 44 | $ - | $ 20 | $ - | $ 880 | $ 880 | | | Flow control valves |
| EA | 44 | $ - | $ 45 | $ - | $ 1,980 | $ 1,980 | | | In-line sample ports |
| EA | 4 | $ - | $ 294 | $ - | $ 1,176 | $ 1,176 | | | Transfer pumps |
| ft | 200 | $ - | $ 2 | $ - | $ 360 | $ 360 | | | Waste water disposal piping, 3/4 in flex tubing |
| ft | 60 | $ - | $ 9 | $ - | $ 516 | $ 516 | | | Connection of air stripper (6 in PVC) |
| | | | | | | | **$ 11,944** | | **Total Above Ground Piping** |
| | | | | | | | **$ 117,854** | | **Total Installation of Equipment and Appurtenances** |

**Equipment Ownership and Rental**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 60,606 | $ - | $ 60,606 | $ 60,606 | | Air stripper incl. blower |
| EA | 1 | | $ 368.00 | $ - | $ 368 | $ 368 | | 250 gal mixing tank |
| | | | | | | | $ 60,974 | **Total Equipment Ownership and Rental Cost** |

**Startup and Testing**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| hrs | 96 | $ 30 | $ - | $ 2,880 | $ - | $ 2,880 | | | Operator Training (6 people field crew) |
| hrs | 280 | $ 50 | $ - | $ 14,000 | $ - | $ 14,000 | | | System shake-down, well testing, etc. |
| | | | | | | | $ 16,880 | | **Total Startup and Testing** |

**Other (non-process related)**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 4,800 | $ - | $ 4,800 | $ 4,800 | | | Office and admin. equipment (computer, printer, etc) |
| EA | 6 | $ - | $ 550 | $ - | $ 3,300 | $ 3,300 | | | H&S training (OSHA) |
| EA | 1 | $ - | $ 3,200 | $ - | $ 3,200 | $ 3,200 | | | Field safety equipment, various |
| | | | | | | | $ 11,300 | | **Total Other** |

**$ 397,406 TOTAL CAPITAL (year 1)**

## 1st Year OPERATING AND MAINTENANCE COST (hypothetical full-scale system)

**Labor**

Assume: 1 person, 8 hrs/day, 7 days/week, SCADA technology is used

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| hrs | 480 | $ 30 | $ - | $ 14,386 | $ - | $ 14,386 | | Operating labor |
| hrs | 959 | $ 30 | $ - | $ 28,771 | $ - | $ 28,771 | | Monitoring labor |
| hrs | 168 | $ 90 | $ - | $ 15,120 | $ - | $ 15,120 | | Supervision |
| | | | | | | | $ 58,277 | **Total Labor Cost** |

**Materials**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| LB | 407440 | $ - | $ 2.00 | $ - | $ 814,880 | $ 814,880 | | Cyclodextrin, tech grade |
| EA | 1 | $ 15,000 | $ - | $ 15,000 | $ - | $ 15,000 | | Replacement membranes for UF unit |
| months | 6 | $ - | $ 500 | $ - | $ 3,000 | $ 3,000 | | H&S survey, personal protective equip. |
| month | 6 | $ - | $ 1,000 | $ - | $ 6,000 | $ 6,000 | | Consumable supplies, repairs |
| | | | | | | | $ 838,880 | **Total Material Cost** |

**Utilities and Fuel**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| KWH | 106128 | $ - | $ 0.05725 | $ - | $ 6,076 | $ 6,076 | | Electricity cost |
| gal | 1605 | $ - | $ 2.00 | $ - | $ 3,209 | $ 3,209 | | Fuel for diesel electric generator |
| 1000 gal | 264 | $ - | $ 0.44 | $ - | $ 116 | $ 116 | | Water |
| | | | | | | | $ 9,401 | **Total Utilities and Fuel Cost** |

**Equipment Ownership and Rental**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| months | 6 | | $ 26,250 | $ - | $ 157,500 | $ 157,500 | | UF membrane unit for CD reconcentration |
| EA | 6 | | $ 1,497 | $ - | $ 8,982 | $ 8,982 | | Diesel electric generator (480 V, 22KW) |
| months | 6 | | $ 832 | $ - | $ 4,992 | $ 4,992 | | Suspended solid filter system |
| months | 12 | | $ 1,197 | $ - | $ 14,368 | $ 14,368 | | 2 x 21,000 gal holding tank |
| months | 6 | $ - | $ 8,490 | $ - | $ 50,937 | $ 50,937 | | Air activated carbon filter system |
| | | | | | | | $ 236,779 | **Total Equipment Ownership and Rental Cost** |

**Performance Testing and Analysis**

***Analysis Cost - off-site***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 210 | | $ 85 | $ - | $ 17,850 | $ 17,850 | | VOC analysis (short list) |
| | | | | | | | $ 17,850 | **Total Performance Testing and Analysis - off site** |

***Analysis Cost - on-site***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 1050 | | $ 15 | $ - | $ 15,750 | $ 15,750 | | CD analysis (TOC method) |
| EA | 26 | | $ 60 | $ - | $ 1,560 | $ 1,560 | | Field parameters (set of pH, DO, T, EC), once per week |
| | | | | | | | $ 17,310 | **Total Performance Testing and Analysis - on site** |

**Other (non-process related)**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| hrs | 80 | | $ 125 | $ - | $ 10,000 | $ 10,000 | | Final report preparation (Project Manager) |
| EA | 1 | $ - | $ 4,496 | $ - | $ 4,496 | $ 4,496 | | PID for H&S survey, personal protective equip. |
| months | 6 | | $ 54 | $ - | $ 324 | $ 324 | | On-site sanitation (rental) |
| EA | 130 | $ - | $ 25 | $ - | $ 3,250 | $ 3,250 | | S/H of samples (5 shipments per week) |
| | | | | | | | $ 18,070 | Total Other (non-process related) |

**$ 959,788 TOTAL O&M (year 1)**

**OTHER TECHNOLGOY SPECIFIC COSTS (hypothetical full-scale system)**

**Disposal of Hazardeous Waste**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 16,500 | $ - | $ 16,500 | $ 16,500 | | | Off-site disposal of drill cuttings |
| months | 6 | $ - | $ 250 | $ - | $ 1,500 | $ 1,500 | | | Off-site disposal of liquid wastes |
| | | | | | | | **$ 18,000** | **Total Disposal of Hazardeous Waste** | |

**Site Restoration**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| hrs | 24 | $ 30 | | $ 720 | $ - | $ 720 | | Field crew |
| hrs | 4 | $ 90 | | $ 360 | $ - | $ 360 | | Supervision |
| | | | | | | | **$ 1,080** | **Total Site Restoration** |
| | | | | | | | **$ 19,080** | **TOTAL OTHER TECHNOL. SPECIFIC COSTS (year 2)** |

## Summary

| **2,500 ft2 Full-scale CDEF implementation<br>Multi-well push-pull with UF in batch mode (6 months)** | | |
|---|---|---|
| **Cost Category** | **Sub Category** | **Cost ($)** |
| | **FIXED COSTS** | |
| ***1. Capital Cost*** | Mobilization/Demobilization | $ 17,928 |
| | Planning/Preparation | $ 52,020 |
| | Site Investigation | $ 101,850 |
| | Site Work | $ 18,600 |
| | Equipment Cost - Structures | $ - |
| | Equipment Cost - Process Equipment | $ 60,974 |
| | Star-up and Testing | $ 16,880 |
| | Other - Non Process Equipment | $ 11,300 |
| | Other - Installation | $ 117,854 |
| | Other - Engineering (1) | $ - |
| | Other - Management Support (2) | $ - |
| | **Sub-Total:** | **$ 397,406** |
| | **VARIABLE COSTS** | |
| ***2. Variable Cost*** | Labor | $ 58,277 |
| | Materials / Consumables | $ 838,880 |
| | Utilities / Fuel | $ 9,401 |
| | Equipment Cost (rental) | $ 236,779 |
| | Chemical Analysis | $ 35,160 |
| | Other | $ 18,070 |
| | **Sub-Total:** | **$ 1,196,567** |
| ***3. Other Technology Specific Cost*** | Disposal of well cuttings | $ 16,500 |
| | Disposal of liquid waste | $ 1,500 |
| | Site Restoration | $ 1,080 |
| | **Sub-Total:** | **$ 19,080** |
| | **TOTAL COSTS** | |
| | ***Total Technology Cost*** | **$ 1,613,053** |
| | ***Quantity Treated - VOC mass*** | 1415 |
| | ***Unit Cost*** | **$ 1,140** |

***(1) Included in planning/preparation***
***(2) Included in labor cost***

## Cyclodextrin Enhanced Flushing at a hypothetical site

## CAPITAL COST (hypothetical full-scale system)

### Assumptions

Treatment approach: **Mulit-well push-pull with UF in continuous mode**

| | | | |
|---|---|---|---|
| Flushing Vol: | 109 m3 | Power Consum $ | 0.05725 |
| Soil mass: | 600 tons | Cost / KWH | |
| Area: | 234 m2 | Note: Electrical power for UF is provided by generators. | |
| Project duration: | 2 months | | |

Number of wells, type and depth needed for remediation

| | | |
|---|---|---|
| 40 | Injection/extraction wells | 22.5 ft |

### DNAPL Source Zone Characterization

Assume: approximate extent of plume is already known

| Units | No of units | Unit labor cost (hr) | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 1,600 | $ - | $ 1,600 | $ 1,600 | | | Mob/Demob Geoprobe/Membrane Interface Probe (MIP) |
| EA | 10 | $ - | $ 3,500 | $ - | $ 35,000 | $ 35,000 | | | MIP with Electrical Conductivity |
| EA | 40 | $ 95 | $ - | $ 3,800 | $ - | $ 3,800 | | | Operator per diem |
| EA | 20 | $ - | $ 1,250 | $ - | $ 25,000 | $ 25,000 | | | In Situ GW/Soil sampling |
| EA | 75 | $ - | $ 126 | $ - | $ 9,450 | $ 9,450 | | | Lab Analysis (TCL Volatile Organic Compound) |
| EA | 480 | $ 50 | $ - | $ 24,000 | $ - | $ 24,000 | | | Labor (2 Person Field Crew) |
| EA | 15 | $ - | $ 200 | $ - | $ 3,000 | $ 3,000 | | | Equipment and Expendables |
| | | | | | | | $ 101,850 | | **Total DNAPL Source Zone Characterization** |

### Treatability Study (Site soil testing)

| Units | No of units | Unit labor cost (hr) | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 120 | $ 85 | $ - | $ 10,200 | $ - | $ 10,200 | | | Lab techician (soil column tests) |
| EA | 1 | $ - | $ 2,550 | $ - | $ 2,550 | $ 2,550 | | | Lab equipment |
| EA | 24 | $ 125 | | $ 3,000 | $ - | $ 3,000 | | | Report preparation |
| | | | | | | | $ 15,750 | | **Total Cyclodextrin Selection** |

### Engineering, Design, and Modeling

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 144 | 125 | $ 1,770 | $ 22,000 | $ 1,770 | $ 23,770 | | | Work Plan, H&S plan, Site Management Plan (Project manager) |
| EA | 1 | $ - | $ 12,500 | $ - | $ 12,500 | $ 12,500 | | | Permits and licences, estimated |
| | | | | | | | $ 36,270 | | **Total Engineering, Design, and Modeling** |

### Technology Mobilization and Demobilizatior

Assume: Local contractors perform field work

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| hrs | 280 | $ 25 | $ - | $ 7,000 | $ - | $ 7,000 | | | Travel to and from site (incl. accommodation) |
| EA | 2 | $ - | $ 5,464 | $ - | $ 10,928 | $ 10,928 | | | Freight (Palletizing, loading, and shipping of equipmemt) |
| | | | | | | | $ 17,928 | | **Tota Technology Mobilization and Demobilizatior** |

### Site Work

*Site Set-up*

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 1,000 | $ - | $ 1,000 | $ 1,000 | | | Secondary containment (berm) |
| EA | 1 | $ - | $ 1,450 | $ - | $ 1,400 | $ 1,400 | | | Electricity hook-up |
| EA | 540 | $ 30 | $ - | $ 16,200 | $ - | $ 16,200 | | | Plumbing |
| | | | | | | | $ 18,600 | | **Total Site Set-up** |

### Installation of Equipment and Appurtenances

*Well Field Installation*

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| ft | 900 | $ - | $ 77 | $ - | $ 69,030 | $ 69,030 | | | Injection/Extraction well installation |
| EA | 40 | $ - | $ 552 | $ - | $ 22,080 | $ 22,080 | | | Grunfos submersible pumps (Model 5S) |
| EA | 1 | $ - | $ 14,800 | $ - | $ 14,800 | $ 14,800 | | | SCADA system, automated flow control |
| | | | | | | | $ 105,910 | | **Total Well Installation** |

*Above Ground Plumbing*

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| ft | 2000 | $ - | $ 2 | $ - | $ 3,600 | $ 3,600 | | | Well piping, 3/4 in PVC and flex tubing |
| EA | 44 | $ - | $ 78 | $ - | $ 3,432 | $ 3,432 | | | Flowmeters |
| EA | 44 | $ - | $ 20 | $ - | $ 880 | $ 880 | | | Flow control valves |
| EA | 44 | $ - | $ 45 | $ - | $ 1,980 | $ 1,980 | | | In-line sample ports |
| EA | 4 | $ - | $ 294 | $ - | $ 1,176 | $ 1,176 | | | Transfer pumps |
| ft | 200 | $ - | $ 2 | $ - | $ 360 | $ 360 | | | Waste water disposal piping, 3/4 in flex tubing |
| ft | 60 | $ - | $ 9 | $ - | $ 516 | $ 516 | | | Connection of air stripper (6 in PVC) |
| | | | | | | | $ 11,944 | | **Total Above Ground Piping** |
| | | | | | | | $ 117,854 | | **Total Installation of Equipment and Appurtenances** |

**Equipment Ownership and Rental**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 60,606 | $ - | $ 60,606 | $ 60,606 | | Air stripper incl. blower |
| EA | 1 | | $ 368.00 | $ - | $ 368 | $ 368 | | 250 gal mixing tank |
| | | | | | | | $ 60,974 | **Total Equipment Ownership and Rental Cost** |

**Startup and Testing**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| hrs | 96 | $ 30 | $ - | $ 2,880 | $ - | $ 2,880 | | | Operator Training (6 people field crew) |
| hrs | 280 | $ 50 | $ - | $ 14,000 | $ - | $ 14,000 | | | System shake-down, well testing, etc. |
| | | | | | | | $ 16,880 | | **Total Startup and Testing** |

**Other (non-process related)**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 4,800 | $ - | $ 4,800 | $ 4,800 | | | Office and admin. equipment (computer, printer, etc) |
| EA | 3 | $ - | $ 550 | $ - | $ 1,650 | $ 1,650 | | | H&S training (OSHA) |
| EA | 1 | $ - | $ 1,600 | $ - | $ 1,600 | $ 1,600 | | | Field safety equipment, various |
| | | | | | | | $ 8,050 | | **Total Other** |

**$ 394,156 TOTAL CAPITAL (year 1)**

## 1st Year OPERATING AND MAINTENANCE COST (hypothetical full-scale system)

**Labor**

Assume: 1 person, 8 hrs/day, 7 days/week, SCADA technology is used

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| hrs | 160 | $ 30 | $ - | $ 4,795 | $ - | $ 4,795 | | Operating labor |
| hrs | 320 | $ 30 | $ - | $ 9,590 | $ - | $ 9,590 | | Monitoring labor |
| hrs | 96 | $ 90 | $ - | $ 8,640 | $ - | $ 8,640 | | Supervision |
| | | | | | | | $ 23,026 | **Total Labor Cost** |

**Materials**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| LB | 896500 | $ - | $ 2.00 | $ - | $ 1,793,000 | $ 1,793,000 | | Cyclodextrin, tech grade |
| months | 2 | $ - | $ 500 | $ - | $ 1,000 | $ 1,000 | | H&S survey, personal protective equip. |
| month | 2 | $ - | $ 1,000 | $ - | $ 2,000 | $ 2,000 | | Consumable supplies, repairs |
| | | | | | | | $ 1,796,000 | **Total Material Cost** |

**Utilities and Fuel**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| KWH | 35376 | $ - | $ 0.05725 | $ - | $ 2,025 | $ 2,025 | | Electricity cost |
| gal | 1872 | $ - | $ 2.00 | $ - | $ 3,744 | $ 3,744 | | Fuel for diesel electric generator |
| 1000 gal | 88 | $ - | $ 0.44 | $ - | $ 39 | $ 39 | | Water |
| | | | | | | | $ 5,808 | **Total Utilities and Fuel Cost** |

**Equipment Ownership and Rental**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| months | 2 | $ - | $ 30,000 | $ - | $ 60,000 | $ 60,000 | | UF membrane unit for CD reconcentration |
| months | 2 | $ - | $ 1,497 | $ - | $ 2,994 | $ 2,994 | | Diesel electric generator (480 V, 22KW) |
| months | 2 | $ - | $ 997 | $ - | $ 1,993 | $ 1,993 | | PID for H&S survey |
| months | 2 | $ - | $ 832 | $ - | $ 1,664 | $ 1,664 | | Suspended solid filter system |
| months | 2 | $ - | $ 1,197 | $ - | $ 2,395 | $ 2,395 | | 21,000 gal holding tank |
| months | 2 | $ - | $ 8,490 | $ - | $ 16,979 | $ 16,979 | | Air activated carbon filter system |
| | | | | | | | $ 86,025 | **Total Equipment Ownership and Rental Cost** |

**Performance Testing and Analysis**

***Analysis Cost - off-site***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 60 | $ - | $ 85 | $ - | $ 5,100 | $ 5,100 | | VOC analysis (short list) |
| | | | | | | | $ 5,100 | **Total Performance Testing and Analysis - off site** |

***Analysis Cost - on-site***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 120 | $ 15 | $ - | $ 1,800 | $ - | $ 1,800 | | CD analysis (TOC method) |
| EA | 8 | $ - | $ 60 | $ - | $ 480 | $ 480 | | Field parameters (set of pH, DO, T, EC), once per week |
| | | | | | | | $ 2,280 | **Total Performance Testing and Analysis - on site** |

**Other (non-process related)**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| hrs | 64 | $ - | $ 125 | $ - | $ 8,000 | $ 8,000 | | Final report preparation (Project Manager) |
| months | 2 | $ - | $ 54 | $ - | $ 108 | $ 108 | | On-site sanitation (rental) |
| EA | 10 | $ - | $ 25 | $ - | $ 250 | $ 250 | | S/H of samples (5 shipments per week) |
| | | | | | | | $ 8,358 | Total Other (non-process related) |

**$ 1,840,572 TOTAL O&M (year 1)**

**OTHER TECHNOLGOY SPECIFIC COSTS (hypothetical full-scale system)**

**Disposal of Hazardeous Waste**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 16,500 | $ - | $ 16,500 | $ 16,500 | | | Off-site disposal of drill cuttings |
| months | 2 | $ - | $ 250 | $ - | $ 500 | $ 500 | | | Off-site disposal of liquid wastes |
| | | | | | | | **$ 17,000** | | **Total Disposal of Hazardeous Waste** |

**Site Restoration**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| hrs | 24 | $ 30 | | $ 720 | $ - | $ 720 | | Field crew |
| hrs | 4 | $ 90 | | $ 360 | $ - | $ 360 | | Supervision |
| | | | | | | | **$ 1,080** | **Total Site Restoration** |
| | | | | | | | **$ 18,080** | **TOTAL OTHER TECHNOL. SPECIFIC COSTS (year 2)** |

## Summary

| **2,500 ft2 Full-scale CDEF implementation<br>Multi-well push-pull with UF in continuous mode (2 months)** | | |
|---|---|---|
| **Cost Category** | **Sub Category** | **Cost ($)** |
| | **FIXED COSTS** | |
| ***1. Capital Cost*** | Mobilization/Demobilization | $ 17,928 |
| | Planning/Preparation (1) | $ 52,020 |
| | Site Investigation | $ 101,850 |
| | Site Work | $ 18,600 |
| | Equipment Cost - Structures | $ - |
| | Equipment Cost - Process Equipment | $ 60,974 |
| | Star-up and Testing | $ 16,880 |
| | Other - Non Process Equipment | $ 8,050 |
| | Other - Installation | $ 117,854 |
| | Other - Engineering (1) | $ - |
| | Other - Management Support (2) | $ - |
| | **Sub-Total:** | **$ 394,156** |
| | **VARIABLE COSTS** | |
| ***2. Variable Cost*** | Labor | $ 23,026 |
| | Materials / Consumables | $ 1,796,000 |
| | Utilities / Fuel | $ 5,808 |
| | Equipment Cost (rental) | $ 86,025 |
| | Chemical Analysis | $ 7,380 |
| | Other | $ 8,358 |
| | **Sub-Total:** | **$ 1,926,597** |
| ***3. Other Technology Specific Cost*** | Disposal of well cuttings | $ 16,500 |
| | Disposal of liquid waste | $ 500 |
| | Site Restoration | $ 1,080 |
| | **Sub-Total:** | **$ 18,080** |
| | **TOTAL COSTS** | |
| | ***Total Technology Cost*** | **$ 2,338,833** |
| | ***Quantity Treated - VOC mass (lbs)*** | 1415 |
| | ***Unit Cost (per lbs VOC removed and treated)*** | **$ 1,653** |

***(1) Included in planning/preparation***
***(2) Included in labor cost***

## Cyclodextrin Enhanced Flushing at a hypothetical site

### CAPITAL COST (hypothetical full-scale system)

**Assumptions**

Treatment approach: **Multi-well push-pull with no UF system (no reuse)**

| | | | | |
|---|---|---|---|---|
| Flushing Vol: | 109 | m3 | Power Consu | $ 0.05725 |
| Soil mass: | 600 | tons | Cost / KWH | |
| Area: | 234 | m2 | | |
| Project duration: | 2 | months | | |

Number of wells, type and depth needed for remediation

40 Injection/extraction wells 22.5 ft

**DNAPL Source Zone Characterization**

Assume: approximate extent of plume is already known

| Units | No of units | Unit labor cost (hr) | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 1,600 | $ - | $ 1,600 | $ 1,600 | | | Mob/Demob Geoprobe/Membrane Interface Probe (MIP) |
| EA | 10 | $ - | $ 3,500 | $ - | $ 35,000 | $ 35,000 | | | MIP with Electrical Conductivity |
| EA | 40 | $ 95 | $ - | $ 3,800 | $ - | $ 3,800 | | | Operator per diem |
| EA | 20 | $ - | $ 1,250 | $ - | $ 25,000 | $ 25,000 | | | In Situ GW/Soil sampling |
| EA | 75 | $ - | $ 126 | $ - | $ 9,450 | $ 9,450 | | | Lab Analysis (TCL Volatile Organic Compound) |
| EA | 480 | $ 50 | $ - | $ 24,000 | $ - | $ 24,000 | | | Labor (2 Person Field Crew) |
| EA | 15 | $ - | $ 200 | $ - | $ 3,000 | $ 3,000 | | | Equipment and Expendables |
| | | | | | | | **$ 101,850** | | **Total DNAPL Source Zone Characterization** |

**Treatability Study (Site soil testing)**

| Units | No of units | Unit labor cost (hr) | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 120 | $ 85 | $ - | $ 10,200 | $ - | $ 10,200 | | | Lab techician (soil column tests) |
| EA | 1 | $ - | $ 2,550 | $ - | $ 2,550 | $ 2,550 | | | Lab equipment |
| EA | 24 | $ 125 | | $ 3,000 | $ - | $ 3,000 | | | Report preparation |
| | | | | | | | **$ 15,750** | | **Total Cyclodextrin Selection** |

**Engineering, Design, and Modeling**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 120 | $ 125 | $ 1,770 | $ 22,000 | $ 1,770 | $ 23,770 | | | Work Plan, H&S plan, Site Management Plan (Project manager) |
| EA | 1 | $ - | $ 12,500 | $ - | $ 12,500 | $ 12,500 | | | Permits and licences, estimated |
| | | | | | | | **$ 36,270** | | **Total Engineering, Design, and Modeling** |

**Technology Mobilization and Demobilization**

Assume: Local contractors perform field work

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| hrs | 280 | $ 25 | | $ 7,000 | $ - | $ 7,000 | | | Travel to and from site (incl. accommodation) |
| EA | 2 | $ - | $ 1,964 | $ - | $ 3,928 | $ 3,928 | | | Freight (Palletizing, loading, and shipping of equipmemt) |
| | | | | | | | **$ 10,928** | | **Total Technology Mobilization, Setup, and Demobilization** |

**Site Work**

***Site Set-up***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 1,000 | $ - | $ 1,000 | $ 1,000 | | | Secondary containment (berm) |
| EA | 1 | $ - | $ 1,450 | $ - | $ 1,400 | $ 1,400 | | | Electricity hook-up |
| EA | 516 | $ 30 | $ - | $ 15,480 | $ - | $ 15,480 | | | Plumbing |
| | | | | | | | **$ 17,880** | | **Total Site Set-up** |

**Installation of Equipment and Appurtenances**

***Well Field Installation***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| ft | 900 | $ - | $ 77 | $ - | $ 69,030 | $ 69,030 | | | Injection/Extraction well installation |
| EA | 40 | $ - | $ 552 | $ - | $ 22,080 | $ 22,080 | | | Grunfos submersible pumps (Model 5S) |
| EA | 1 | $ - | $ 14,800 | $ - | $ 14,800 | $ 14,800 | | | SCADA system, automated flow control |
| | | | | | | | **$ 105,910** | | **Total Well Installation** |

***Above Ground Plumbing***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| ft | 1800 | $ - | $ 2 | $ - | $ 3,240 | $ 3,240 | | | Well piping, 3/4 in PVC and flex tubing |
| EA | 44 | $ - | $ 78 | $ - | $ 3,432 | $ 3,432 | | | Flowmeters |
| EA | 44 | $ - | $ 20 | $ - | $ 880 | $ 880 | | | Flow control valves |
| EA | 44 | $ - | $ 45 | $ - | $ 1,980 | $ 1,980 | | | In-line sample ports |
| EA | 4 | $ - | $ 294 | $ - | $ 1,176 | $ 1,176 | | | Transfer pumps |
| ft | 200 | $ - | $ 2 | $ - | $ 360 | $ 360 | | | Waste water disposal piping, 3/4 in flex tubing |
| ft | 60 | $ - | $ 9 | $ - | $ 516 | $ 516 | | | Connection of air stripper (6 in PVC) |
| | | | | | | | **$ 11,584** | | **Total Above Ground Piping** |
| | | | | | | | **$ 117,494** | | **Total Installation of Equipment and Appurtenances** |

**Equipment Ownership and Rental**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 60,606 | $ - | $ 60,606 | $ 60,606 | | Air stripper incl. blower |
| EA | 1 | | $ 368.00 | $ - | $ 368 | $ 368 | | 250 gal mixing tank |
| | | | | | | | $ 60,974 | **Total Equipment Ownership and Rental Cost** |

**Startup and Testing**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| hrs | 48 | $ 30 | $ - | $ 1,440 | $ - | $ 1,440 | | | Operator Training (6 people field crew) |
| hrs | 232 | $ 50 | $ - | $ 11,600 | $ - | $ 11,600 | | | System shake-down, well testing, etc. |
| | | | | | | | $ 13,040 | | **Total Startup and Testing** |

**Other (non-process related)**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 4,800 | $ - | $ 4,800 | $ 4,800 | | | Office and admin. equipment (computer, printer, etc) |
| EA | 3 | $ - | $ 550 | $ - | $ 1,650 | $ 1,650 | | | H&S training (OSHA) |
| EA | 1 | $ - | $ 1,600 | $ - | $ 1,600 | $ 1,600 | | | Field safety equipment, various |
| | | | | | | | $ 8,050 | | **Total Other** |

**$ 382,236 TOTAL CAPITAL (year 1)**

## 1st Year OPERATING AND MAINTENANCE COST (hypothetical full-scale system)

**Labor**

Assume: 1 person, 5 hrs/day, 7 days/week, SCADA technology is used

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| hrs | 100 | $ 30 | $ - | $ 3,000 | $ - | $ 3,000 | | Operating labor |
| hrs | 300 | $ 30 | $ - | $ 9,000 | $ - | $ 9,000 | | Monitoring labor |
| hrs | 168 | $ 90 | $ - | $ 15,120 | $ - | $ 15,120 | | Supervision |
| | | | | | | | $ 27,120 | **Total Labor Cost** |

**Materials**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| LB | 2407460 | $ - | $ 2.00 | $ - | $ 4,814,920 | $ 4,814,920 | | Cyclodextrin, tech grade |
| months | 2 | $ - | $ 500 | $ - | $ 1,000 | $ 1,000 | | H&S survey, personal protective equip. |
| month | 2 | $ - | $ 1,000 | $ - | $ 2,000 | $ 2,000 | | Consumable supplies, repairs |
| | | | | | | | $ 4,817,920 | **Total Material Cost** |

**Utilities and Fuel**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| KWH | 106128 | $ - | $ 0.05725 | $ - | $ 6,076 | $ 6,076 | | Electricity cost |
| 1000 gal | 88 | $ - | $ 0.44 | $ - | $ 39 | $ 39 | | Water |
| | | | | | | | $ 6,115 | **Total Utilities and Fuel Cost** |

**Equipment Ownership and Rental**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| months | 2 | $ - | $ 30,000 | $ - | $ 60,000 | $ 60,000 | | UF membrane unit for CD reconcentration |
| months | 2 | $ - | $ 1,497 | $ - | $ 2,994 | $ 2,994 | | Diesel electric generator (480 V, 22KW) |
| months | 2 | $ - | $ 997 | $ - | $ 1,993 | $ 1,993 | | PID for H&S survey |
| months | 2 | $ - | $ 832 | $ - | $ 1,664 | $ 1,664 | | Suspended solid filter system |
| months | 2 | $ - | $ 1,197 | $ - | $ 2,395 | $ 2,395 | | 21,000 gal holding tank |
| months | 2 | $ - | $ 8,490 | $ - | $ 16,979 | $ 16,979 | | Air activated carbon filter system |
| | | | | | | | $ 86,025 | **Total Equipment Ownership and Rental Cost** |

**Performance Testing and Analysis**

***Analysis Cost - off-site***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 60 | $ - | $ 85 | $ - | $ 5,100 | $ 5,100 | | VOC analysis (short list) |
| | | | | | | | $ 5,100 | **Total Performance Testing and Analysis - off site** |

***Analysis Cost - on-site***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 120 | $ - | $ 15 | $ - | $ 1,800 | $ 1,800 | | CD analysis (TOC method) |
| EA | 8 | | $ 60 | $ - | $ 480 | $ 480 | | Field parameters (set of pH, DO, T, EC), once per week |
| | | | | | | | $ 2,280 | **Total Performance Testing and Analysis - on site** |

**Other (non-process related)**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| hrs | 64 | $ - | $ 125 | $ - | $ 8,000 | $ 8,000 | | Semi-annual report preparation (Project Manager) |
| months | 2 | $ - | $ 54 | $ - | $ 108 | $ 108 | | On-site sanitation (rental) |
| EA | 20 | $ - | $ 25 | $ - | $ 500 | $ 500 | | S/H of samples (5 shipments per week) |
| | | | | | | | $ 8,608 | Total Other (non-process related) |

**$ 4,867,143 TOTAL O&M (year 1)**

**OTHER TECHNOLGOY SPECIFIC COSTS (hypothetical full-scale system)**

**Disposal of Hazardeous Waste**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 16,500 | $ - | $ 16,500 | $ 16,500 | | | Off-site disposal of drill cuttings |
| months | 2 | $ - | $ 250 | $ - | $ 500 | $ 500 | | | Off-site disposal of liquid wastes |
| | | | | | | | **$ 17,000** | | **Total Disposal of Hazardeous Waste** |

**Site Restoration**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| hrs | 24 | $ 30 | | $ 720 | $ - | $ 720 | | Field crew |
| hrs | 4 | $ 90 | | $ 360 | $ - | $ 360 | | Supervision |
| | | | | | | | **$ 1,080** | **Total Site Restoration** |
| | | | | | | | **$ 18,080** | **TOTAL OTHER TECHNOL. SPECIFIC COSTS (year 2)** |

## Summary

| **2,500 ft2 Full-scale CDEF implementation<br>Multi-well push-pull with no UF system (no reuse) (2 Months)** | | |
|---|---|---|
| **Cost Category** | **Sub Category** | **Cost ($)** |
| | **FIXED COSTS** | |
| ***1. Capital Cost*** | Mobilization/Demobilization | $ 10,928 |
| | Planning/Preparation | $ 52,020 |
| | Site Investigation | $ 101,850 |
| | Site Work | $ 17,880 |
| | Equipment Cost - Structures | $ - |
| | Equipment Cost - Process Equipment | $ 60,974 |
| | Star-up and Testing | $ 13,040 |
| | Other - Non Process Equipment | $ 8,050 |
| | Other - Installation | $ 117,494 |
| | Other - Engineering (1) | $ - |
| | Other - Management Support (2) | $ - |
| | **Sub-Total:** | **$ 382,236** |
| | **VARIABLE COSTS** | |
| ***2. Variable Cost*** | Labor | $ 27,120 |
| | Materials / Consumables | $ 4,817,920 |
| | Utilities / Fuel | $ 6,115 |
| | Equipment Cost (rental) | $ 86,025 |
| | Chemical Analysis | $ 7,380 |
| | Other | $ 8,608 |
| | **Sub-Total:** | **$ 4,953,168** |
| ***3. Other Technology Specific Cost*** | Disposal of well cuttings | $ 16,500 |
| | Disposal of liquid waste | $ 500 |
| | Site Restoration | $ 1,080 |
| | **Sub-Total:** | **$ 18,080** |
| | **TOTAL COSTS** | |
| | ***Total Technology Cost*** | **$ 5,353,484** |
| | ***Quantity Treated - VOC mass (lbs)*** | 1415 |
| | ***Unit Cost (per lbs VOC removed and treated)*** | **$ 3,783** |

***(1) Included in planning/preparation***
***(2) Included in labor cost***

## Cyclodextrin Enhanced Flushing at a hypothetical site

## CAPITAL COST (hypothetical full-scale system)

### Assumptions

Treatment approach: **Line-drive (I/E) with UF in continous mode (Year 1)**

| | | |
|---|---|---|
| Flushing Vol: | 109 | m3 |
| Soil mass: | 600 | tons |
| Area: | 234 | m2 |
| Project duration: | 19 | months |

Power Consumption in: KW
Cost / KWH $ 0.05725
Note: Electrical power for UF is provided by generators.

Number of wells, type and depth needed for remediation

| | | |
|---|---|---|
| 14 | Injection wells | 22.5 ft |
| 24 | Extraction wells | 22.5 ft |
| 8 | Hydraulic control wells | 22.5 ft |

### DNAPL Source Zone Characterization

Assume: approximate extent of plume is already known

| Units | No of units | Unit labor cost (hr) | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 1,600 | $ - | $ 1,600 | $ 1,600 | | | Mob/Demob Geoprobe/Membrane Interface Probe (MIP) |
| EA | 10 | $ - | $ 3,500 | $ - | $ 35,000 | $ 35,000 | | | MIP with Electrical Conductivity |
| EA | 40 | $ 95 | $ - | $ 3,800 | $ - | $ 3,800 | | | Operator per diem |
| EA | 20 | $ - | $ 1,250 | $ - | $ 25,000 | $ 25,000 | | | In Situ GW/Soil sampling |
| EA | 75 | $ - | $ 126 | $ - | $ 9,450 | $ 9,450 | | | Lab Analysis (TCL Volatile Organic Compound) |
| EA | 480 | $ 50 | $ - | $ 24,000 | $ - | $ 24,000 | | | Labor (2 Person Field Crew) |
| EA | 15 | $ - | $ 200 | $ - | $ 3,000 | $ 3,000 | | | Equipment and Expendables |
| | | | | | | | **$ 101,850** | | **Total DNAPL Source Zone Characterization** |

### Treatability Study (Site soil testing)

| Units | No of units | Unit labor cost (hr) | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 120 | $ 85 | $ - | $ 10,200 | $ - | $ 10,200 | | | Lab techician (soil column tests) |
| EA | 1 | $ - | $ 2,550 | $ - | $ 2,550 | $ 2,550 | | | Lab equipment |
| EA | 24 | $ 125 | | $ 3,000 | $ - | $ 3,000 | | | Report preparation |
| | | | | | | | **$ 15,750** | | **Total Cyclodextrin Selection** |

### Engineering, Design, and Modeling

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 144 | $ 125 | $ 1,770 | $ 22,000 | $ 1,770 | $ 23,770 | | | Work Plan, H&S plan, Site Management Plan (Project manager) |
| EA | 1 | $ - | $ 12,500 | $ - | $ 12,500 | $ 12,500 | | | Permits and licences, estimated |
| | | | | | | | **$ 36,270** | | **Total Engineering, Design, and Modeling** |

### Technology Mobilization and Demobilizatior

Assume: Local contractors perform field work

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| hrs | 280 | $ 25 | | $ 7,000 | $ - | $ 7,000 | | | Travel to and from site (incl. accommodation) |
| EA | 2 | $ - | $ 5,464 | $ - | $ 10,928 | $ 10,928 | | | Freight (Palletizing, loading, and shipping of equipmemt) |
| | | | | | | | **$ 17,928** | | **Total Technology Mobilization and Demobilizatior** |

### Site Work

*Site Set-up*

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 1,000 | $ - | $ 1,000 | $ 1,000 | | | Secondary containment (berm) |
| EA | 1 | $ - | $ 1,450 | $ - | $ 1,400 | $ 1,400 | | | Electricity hook-up |
| EA | 540 | $ 30 | $ - | $ 16,200 | $ - | $ 16,200 | | | Plumbing |
| | | | | | | | **$ 18,600** | | **Total Site Set-up** |

### Installation of Equipment and Appurtenances

*Well Field Installation*

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| ft | 1035 | $ - | $ 77 | $ - | $ 79,385 | $ 79,385 | | | Injection/Extraction well installation |
| EA | 24 | $ - | $ 552 | $ - | $ 13,248 | $ 13,248 | | | Grunfos submersible pumps (Model 5S) |
| EA | 1 | $ - | $ 14,800 | $ - | $ 14,800 | $ 14,800 | | | SCADA system, automated flow control |
| | | | | | | | **$ 107,433** | | **Total Well Installation** |

*Above Ground Plumbing*

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| ft | 2000 | $ - | $ 2 | $ - | $ 3,600 | $ 3,600 | | | Well piping, 3/4 in PVC and flex tubing |
| EA | 46 | $ - | $ 78 | $ - | $ 3,588 | $ 3,588 | | | Flowmeters |
| EA | 50 | $ - | $ 21 | $ - | $ 1,050 | $ 1,050 | | | Flow control valves |
| EA | 38 | $ - | $ 45 | $ - | $ 1,710 | $ 1,710 | | | In-line sample ports |
| EA | 4 | $ - | $ 294 | $ - | $ 1,176 | $ 1,176 | | | Transfer pumps |
| ft | 200 | $ - | $ 2 | $ - | $ 440 | $ 440 | | | Waste water disposal piping, 3/4 in flex tubing |
| ft | 60 | $ - | $ 9 | $ - | $ 516 | $ 516 | | | Connection of air stripper (6 in PVC) |
| | | | | | | | **$ 12,080** | | **Total Above Ground Piping** |
| | | | | | | | **$ 119,513** | | **Total Installation of Equipment and Appurtenances** |

**Equipment Ownership and Rental**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 30,303 | $ - | $ 30,303 | $ 30,303 | | Air stripper incl. blower (200 cfm) |
| EA | 2 | | $ 14,368 | $ - | $ 28,736 | $ 28,736 | | 21,000 gal holding tank |
| EA | 1 | | $ 210,000 | $ - | $ 210,000 | $ 210,000 | | UF membrane unit for CD reconcentration |
| EA | 1 | | $ 6,656 | $ - | $ 6,656 | $ 6,656 | | Suspended solid filter system |
| EA | 1 | | $ 368.00 | $ - | $ 368 | $ 368 | | 250 gal mixing tank |
| EA | 1 | | $ 11,976 | $ - | $ 11,976 | $ 11,976 | | Diesel electric generator (480 V, 22KW) |
| | | | | | | | $ 288,039 | **Total Equipment Ownership and Rental Cost** |

**Startup and Testing**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| hrs | 96 | $ 30 | $ - | $ 2,880 | $ - | $ 2,880 | | | Operator Training (6 people field crew) |
| hrs | 280 | $ 50 | $ - | $ 14,000 | $ - | $ 14,000 | | | System shake-down, well testing, etc. |
| | | | | | | | $ 16,880 | | **Total Startup and Testing** |

**Other (non-process related)**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 4,800 | $ - | $ 4,800 | $ 4,800 | | | Office and admin. equipment (computer, printer, etc) |
| EA | 6 | $ - | $ 550 | $ - | $ 3,300 | $ 3,300 | | | H&S training (OSHA) |
| EA | 1 | $ - | $ 3,200 | $ - | $ 3,200 | $ 3,200 | | | Field safety equipment, various |
| | | | | | | | $ 11,300 | | **Total Other** |

| | |
|---|---|
| **$ 626,130** | **TOTAL CAPITAL (year 1)** |

## 1st Year OPERATING AND MAINTENANCE COST (hypothetical full-scale system)

**Labor**

Assume: 1 person, 8 hrs/day, 7 days/week, SCADA technology is used

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| hrs | 719 | $ 30 | $ - | $ 21,578 | $ - | $ 21,578 | | Operating labor |
| hrs | 1439 | $ 30 | $ - | $ 43,157 | $ - | $ 43,157 | | Monitoring labor |
| hrs | 336 | $ 90 | $ - | $ 30,240 | $ - | $ 30,240 | | Supervision |
| | | | | | | | $ 94,975 | **Total Labor Cost** |

**Materials**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| LB | 1003616.8 | $ - | $ 2.00 | $ - | $ 2,007,234 | $ 2,007,234 | | Cyclodextrin, tech grade |
| EA | 2 | | $ 15,000 | $ - | $ 30,000 | $ 30,000 | | Replacement membranes for UF unit |
| months | 12 | $ - | $ 500 | $ - | $ 6,000 | $ 6,000 | | H&S survey, personal protective equip. |
| month | 12 | $ - | $ 1,000 | $ - | $ 12,000 | $ 12,000 | | Consumable supplies, repairs |
| | | | | | | | $ 2,055,234 | **Total Material Cost** |

**Utilities and Fuel**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| KWH | 231702 | $ - | $ 0.05725 | $ - | $ 13,265 | $ 13,265 | | Electricity cost |
| gal | 11388 | $ - | $ 2.00 | $ - | $ 22,776 | $ 22,776 | | Fuel for diesel electric generator |
| 1000 gal | 528 | $ - | $ 0.44 | $ - | $ 232 | $ 232 | | Water |
| | | | | | | | $ 36,273 | **Total Utilities and Fuel Cost** |

**Equipment Ownership and Rental**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| months | 12 | $ - | $ 8,490 | $ - | $ 101,874 | $ 101,874 | | Air activated carbon filter system |
| | | | | | | | $ 101,874 | **Total Equipment Ownership and Rental Cost** |

**Performance Testing and Analysis**

***Analysis Cost - off-site***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 365 | | $ 85 | $ - | $ 31,025 | $ 31,025 | | VOC analysis (short list) |
| | | | | | | | $ 31,025 | **Total Performance Testing and Analysis - off site** |

***Analysis Cost - on-site***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 730 | | $ 15 | $ - | $ 10,950 | $ 10,950 | | CD analysis (TOC method) |
| EA | 52 | | $ 60 | $ - | $ 3,120 | $ 3,120 | | Field parameters (set of pH, DO, T, EC), once per week |
| | | | | | | | $ 14,070 | **Total Performance Testing and Analysis - on site** |

**Other (non-process related)**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| hrs | 40 | | $ 125 | $ - | $ 5,000 | $ 5,000 | | Semi-annual report preparation (Project Manager) |
| EA | 1 | $ - | $ 4,496 | $ - | $ 4,496 | $ 4,496 | | PID for H&S survey, personal protective equip. |
| months | 12 | | $ 54 | $ - | $ 648 | $ 648 | | On-site sanitation (rental) |
| EA | 260 | $ - | $ 25 | $ - | $ 6,500 | $ 6,500 | | S/H of samples (5 shipments per week) |
| | | | | | | | **$ 16,644** | Total Other (non-process related) |

| | |
|---|---|
| **$ 2,248,221** | **TOTAL O&M (year 1)** |

## OTHER TECHNOLGOY SPECIFIC COSTS (hypothetical full-scale system)

**Disposal of Hazardeous Waste**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 16,500 | $ - | $ 16,500 | $ 16,500 | | | Off-site disposal of drill cuttings |
| months | 12 | $ - | $ 250 | $ - | $ 3,000 | $ 3,000 | | | Off-site disposal of liquid wastes |
| | | | | | | | $ 19,500 | | **Total Disposal of Hazardeous Waste** |

| | |
|---|---|
| **$ 19,500** | **TOTAL OTHER TECHNOL. SPECIFIC COSTS (year 1)** |

**Cyclodextrin Enhanced Flushing at a hypothetical site**

Treatment approach: **Line-drive (I/E) with UF in continous mode (Year 2)**

## CAPITAL COST (hypothetical full-scale system)

No capital (fxed) cost after year 1

## 2nd Year OPERATING AND MAINTENANCE COST (hypothetical full-scale system)

**Labor**

Assume: 1 person, 8 hrs/day, 7 days/week,SCADA technology is used

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| hrs | 420 | $ 30 | $ - | $ 12,587 | $ - | $ 12,587 | | Operating labor |
| hrs | 839 | $ 30 | $ - | $ 25,175 | $ - | $ 25,175 | | Monitoring labor |
| hrs | 196 | $ 90 | $ - | $ 17,640 | $ - | $ 17,640 | | Supervision |
| | | | | | | | $ 55,402 | **Total Labor Cost** |

**Materials**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| LB | 585443.16 | $ - | $ 2.00 | $ - | $ 1,170,886 | $ 1,170,886 | | Cyclodextrin, tech grade |
| EA | 1 | | $ 15,000 | $ - | $ 15,000 | $ 15,000 | | Replacement membranes for UF unit |
| months | 7 | $ - | $ 500 | $ - | $ 3,500 | $ 3,500 | | H&S survey, personal protective equip. |
| month | 7 | $ - | $ 1,000 | $ - | $ 7,000 | $ 7,000 | | Consumable supplies, repairs |
| | | | | | | | $ 1,196,386 | **Total Material Cost** |

**Utilities and Fuel**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| KWH | 59532 | $ - | $ 0.05725 | $ - | $ 3,408 | $ 3,408 | | Electricity cost |
| gal | 6552 | $ - | $ 2.00 | $ - | $ 13,104 | $ 13,104 | | Fuel for diesel electric generator |
| 1000 gal | 308 | $ - | $ 0.44 | $ - | $ 136 | $ 136 | | Water |
| | | | | | | | $ 16,648 | **Total Utilities and Fuel Cost** |

**Equipment Ownership and Rental**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| months | 7 | $ - | $ 8,490 | $ - | $ 59,427 | $ 59,427 | | Air activated carbon filter system |
| | | | | | | | $ 59,427 | **Total Equipment Ownership and Rental Cost** |

**Performance Testing and Analysis**

***Analysis Cost - off-site***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 210 | | $ 85 | $ - | $ 17,850 | $ 17,850 | | VOC analysis (short list) |
| | | | | | | | $ 17,850 | **Total Performance Testing and Analysis - off site** |

***Analysis Cost - on-site***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 420 | | $ 15 | $ - | $ 6,300 | $ 6,300 | | CD analysis (TOC method) |
| EA | 28 | | $ 60 | $ - | $ 1,680 | $ 1,680 | | Field parameters (set of pH, DO, T, EC), once per week |
| | | | | | | | $ 7,980 | **Total Performance Testing and Analysis - on site** |

**Other (non-process related)**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| hrs | 40 | $ 125 | $ - | $ 5,000 | $ - | $ 5,000 | | Semi-annual report preparation (Project Manager) |
| EA | 260 | $ - | $ 25 | $ - | $ 6,500 | $ 6,500 | | S/H of samples (5 shipments per week) |
| months | 7 | | $ 54 | $ - | $ 378 | $ 378 | | On-site sanitation (rental) |
| | | | | | | | $ 11,878 | Total Other (non-process related) |
| | | | | | | | **$ 1,365,571** | **TOTAL O&M (year 2)** |

## OTHER TECHNOLGOY SPECIFIC COSTS (hypothetical full-scale system)

**Disposal of Hazardeous Waste**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| months | 7 | $ - | $ 300 | $ - | $ 2,100 | $ 2,100 | | | Off-site disposal of liquid wastes |
| | | | | | | | $ 2,100 | | **Total Disposal of Hazardeous Waste** |

**Site Restoration**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| hrs | 24 | $ 30 | | $ 720 | $ - | $ 720 | | Field crew |
| hrs | 4 | $ 90 | | $ 360 | $ - | $ 360 | | Supervision |
| | | | | | | | $ 1,080 | **Total Site Restoration** |
| | | | | | | | **$ 3,180** | **TOTAL OTHER TECHNOL. SPECIFIC COSTS (year 2)** |

## Summary

**2,500 ft3 Full-scale CDEF implementation**
**Line-drive (I/E) with UF in continous mode (19 months)**

| Cost Category | Sub Category | Cost ($) |
|---|---|---|
| | **FIXED COSTS** | |
| ***1. Capital Cost*** | Mobilization/Demobilization | $ 17,928 |
| | Planning/Preparation | $ 52,020 |
| | Site Investigation | $ 101,850 |
| | Site Work | $ 18,600 |
| | Equipment Cost - Structures | $ - |
| | Equipment Cost - Process Equipment | $ 288,039 |
| | Star-up and Testing | $ 16,880 |
| | Other - Non Process Equipment | $ 11,300 |
| | Other - Installation | $ 119,513 |
| | Other - Engineering (1) | $ - |
| | Other - Management Support (2) | $ - |
| | **Sub-Total:** | **$ 626,130** |
| | **VARIABLE COSTS** | |
| ***2. Variable Cost*** | Labor | $ 150,377 |
| | Materials / Consumables | $ 3,251,620 |
| | Utilities / Fuel | $ 52,921 |
| | Equipment Cost (A-carbon, rental) | $ 161,301 |
| | Chemical Analysis | $ 70,925 |
| | Other | $ 28,522 |
| | **Sub-Total:** | **$ 3,715,666** |
| ***3. Other Technology Specific Cost*** | Disposal of well cuttings | $ 16,500 |
| | Disposal of liquid waste | $ 5,100 |
| | Site Restoration | $ 1,080 |
| | **Sub-Total:** | **$ 22,680** |
| | **TOTAL COSTS** | |
| | ***Total Technology Cost*** | **$ 4,364,475** |
| | ***Quantity Treated - VOC mass (lbs)*** | 1415 |
| | ***Unit Cost (per lbs VOC removed and treated)*** | **$ 3,085** |

***(1) Included in planning/preparation***
***(2) Included in labor cost***

## Cyclodextrin Enhanced Flushing at a hypothetical site

## CAPITAL COST (hypothetical full-scale system)

### Assumptions

Treatment approach: **Line-drive (I/E) with no UF (Year 1)**

| | | | |
|---|---|---|---|
| Flushing Vol: | 109 m3 | Power Consum $ Cost / KWH | 0.05725 |
| Soil mass: | 600 tons | | |
| Area: | 234 m2 | Note: Electrical power for UF is provided by generators. | |
| Project duration: | 19 months | | |

Number of wells, type and depth needed for remediation

| | | |
|---|---|---|
| 14 | Injection wells | 22.5 ft |
| 24 | Extraction wells | 22.5 ft |
| 8 | Hydraulic control wells | 22.5 ft |

### DNAPL Source Zone Characterization

Assume: approximate extent of plume is already known

| Units | No of units | Unit labor cost (hr) | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 1,600 | $ - | $ 1,600 | $ 1,600 | | | Mob/Demob Geoprobe/Membrane Interface Probe (MIP) |
| EA | 10 | $ - | $ 3,500 | $ - | $ 35,000 | $ 35,000 | | | MIP with Electrical Conductivity |
| EA | 40 | $ 95 | $ - | $ 3,800 | $ - | $ 3,800 | | | Operator per diem |
| EA | 20 | $ - | $ 1,250 | $ - | $ 25,000 | $ 25,000 | | | In Situ GW/Soil sampling |
| EA | 75 | $ - | $ 126 | $ - | $ 9,450 | $ 9,450 | | | Lab Analysis (TCL Volatile Organic Compound) |
| EA | 480 | $ 50 | $ - | $ 24,000 | $ - | $ 24,000 | | | Labor (2 Person Field Crew) |
| EA | 15 | $ - | $ 200 | $ - | $ 3,000 | $ 3,000 | | | Equipment and Expendables |
| | | | | | | | **$ 101,850** | | **Total DNAPL Source Zone Characterization** |

### Treatability Study (Site soil testing)

| Units | No of units | Unit labor cost (hr) | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 120 | $ 85 | $ - | $ 10,200 | $ - | $ 10,200 | | | Lab techician (soil column tests) |
| EA | 1 | $ - | $ 2,550 | $ - | $ 2,550 | $ 2,550 | | | Lab equipment |
| EA | 24 | $ 125 | | $ 3,000 | $ - | $ 3,000 | | | Report preparation |
| | | | | | | | **$ 15,750** | | **Total Cyclodextrin Selection** |

### Engineering, Design, and Modeling

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 144 | $ 125 | $ 1,770 | $ 22,000 | $ 1,770 | $ 23,770 | | | Work Plan, H&S plan, Site Management Plan (Project manager) |
| EA | 1 | $ - | $ 12,500 | $ - | $ 12,500 | $ 12,500 | | | Permits and licences, estimated |
| | | | | | | | **$ 36,270** | | **Total Engineering, Design, and Modeling** |

### Technology Mobilization and Demobilizatior

Assume: Local contractors perform field work

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| hrs | 280 | $ 25 | | $ 7,000 | $ - | $ 7,000 | | | Travel to and from site (incl. accommodation) |
| EA | 2 | $ - | $ 1,964 | $ - | $ 3,928 | $ 3,928 | | | Freight (Palletizing, loading, and shipping of equipmemt) |
| | | | | | | | **$ 10,928** | | **Total Technology Mobilization and Demobilizatior** |

### Site Work

*Site Set-up*

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 1,000 | $ - | $ 1,000 | $ 1,000 | | | Secondary containment (berm) |
| EA | 1 | $ - | $ 1,450 | $ - | $ 1,400 | $ 1,400 | | | Electricity hook-up |
| EA | 540 | $ 30 | $ - | $ 16,200 | $ - | $ 16,200 | | | Plumbing |
| | | | | | | | **$ 18,600** | | **Total Site Set-up** |

### Installation of Equipment and Appurtenances

*Well Field Installation*

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| ft | 1035 | $ - | $ 77 | $ - | $ 79,385 | $ 79,385 | | | Injection/Extraction well installation |
| EA | 24 | $ - | $ 552 | $ - | $ 13,248 | $ 13,248 | | | Grunfos submersible pumps (Model 5S) |
| EA | 1 | $ - | $ 14,800 | $ - | $ 14,800 | $ 14,800 | | | SCADA system, automated flow control |
| | | | | | | | **$ 107,433** | | **Total Well Installation** |

*Above Ground Plumbing*

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| ft | 1900 | $ - | $ 2 | $ - | $ 3,420 | $ 3,420 | | | Well piping, 3/4 in PVC and flex tubing |
| EA | 46 | $ - | $ 78 | $ - | $ 3,588 | $ 3,588 | | | Flowmeters |
| EA | 50 | $ - | $ 21 | $ - | $ 1,050 | $ 1,050 | | | Flow control valves |
| EA | 42 | $ - | $ 45 | $ - | $ 1,890 | $ 1,890 | | | In-line sample ports |
| EA | 3 | $ - | $ 294 | $ - | $ 882 | $ 882 | | | Transfer pumps |
| ft | 200 | $ - | $ 2 | $ - | $ 360 | $ 360 | | | Waste water disposal piping, 3/4 in flex tubing |
| ft | 60 | $ - | $ 9 | $ - | $ 516 | $ 516 | | | Connection of air stripper (6 in PVC) |
| | | | | | | | **$ 11,706** | | **Total Above Ground Piping** |
| | | | | | | | **$ 119,139** | | **Total Installation of Equipment and Appurtenances** |

**Equipment Ownership and Rental**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 30,303 | $ - | $ 30,303 | $ 30,303 | | Air stripper incl. blower (200 cfm) |
| EA | 2 | $ - | $ 14,368 | $ - | $ 28,736 | $ 28,736 | | 21,000 gal holding tank |
| EA | 1 | $ - | $ 6,656 | $ - | $ 6,656 | $ 6,656 | | Suspended solid filter system |
| EA | 1 | $ - | $ 368.00 | $ - | $ 368 | $ 368 | | 250 gal mixing tank |
| | | | | | | | **$ 66,063** | **Total Equipment Ownership and Rental Cost** |

**Startup and Testing**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| hrs | 48 | $ 30 | $ - | $ 1,440 | $ - | $ 1,440 | | | Operator Training (6 people field crew) |
| hrs | 236 | $ 50 | $ - | $ 11,800 | $ - | $ 11,800 | | | System shake-down, well testing, etc. |
| | | | | | | | **$ 13,240** | | **Total Startup and Testing** |

**Other (non-process related)**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 4,800 | $ - | $ 4,800 | $ 4,800 | | | Office and admin. equipment (computer, printer, etc) |
| EA | 6 | $ - | $ 550 | $ - | $ 3,300 | $ 3,300 | | | H&S training (OSHA) |
| EA | 1 | $ - | $ 3,200 | $ - | $ 3,200 | $ 3,200 | | | Field safety equipment, various |
| | | | | | | | **$ 11,300** | | **Total Other** |

**$ 393,140 TOTAL CAPITAL (year 1)**

## 1st Year OPERATING AND MAINTENANCE COST (hypothetical full-scale system)

**Labor**

Assume: 1 person, 8 hrs/day, 7 days/week, SCADA technology is used

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| hrs | 360 | $ 30 | $ - | $ 10,800 | $ - | $ 10,800 | | Operating labor |
| hrs | 1440 | $ 30 | $ - | $ 43,200 | $ - | $ 43,200 | | Monitoring labor |
| hrs | 336 | $ 90 | $ - | $ 30,240 | $ - | $ 30,240 | | Supervision |
| | | | | | | | **$ 84,240** | **Total Labor Cost** |

**Materials**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| LB | 1780888 | $ - | $ 2.00 | $ - | $ 3,561,777 | $ 3,561,777 | | Cyclodextrin, tech grade |
| months | 12 | $ - | $ 500 | $ - | $ 6,000 | $ 6,000 | | H&S survey, personal protective equip. |
| month | 12 | $ - | $ 1,000 | $ - | $ 12,000 | $ 12,000 | | Consumable supplies, repairs |
| | | | | | | | **$ 3,579,777** | **Total Material Cost** |

**Utilities and Fuel**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| KWH | 231702 | $ - | $ 0.05725 | $ - | $ 13,265 | $ 13,265 | | Electricity cost |
| 1000 gal | 528 | $ - | $ 0.44 | $ - | $ 232 | $ 232 | | Water |
| | | | | | | | **$ 13,497** | **Total Utilities and Fuel Cost** |

**Equipment Ownership and Rental**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| months | 12 | $ - | $ 8,490 | $ - | $ 101,874 | $ 101,874 | | Air activated carbon filter system |
| | | | | | | | **$ 101,874** | **Total Equipment Ownership and Rental Cost** |

**Performance Testing and Analysis**

***Analysis Cost - off-site***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 365 | $ 85 | $ - | $ 31,025 | $ - | $ 31,025 | | VOC analysis (short list) |
| | | | | | | | **$ 31,025** | **Total Performance Testing and Analysis - off site** |

***Analysis Cost - on-site***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 730 | $ 15 | $ - | $ 10,950 | $ - | $ 10,950 | | CD analysis (TOC method) |
| EA | 52 | | $ 60 | $ - | $ 3,120 | $ 3,120 | | Field parameters (set of pH, DO, T, EC), once per week |
| | | | | | | | **$ 14,070** | **Total Performance Testing and Analysis - on site** |

**Other (non-process related)**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| hrs | 40 | $ 125 | $ - | $ 5,000 | $ - | $ 5,000 | | Semi-annual report preparation (Project Manager) |
| EA | 1 | $ - | $ 4,496 | $ - | $ 4,496 | $ 4,496 | | PID for H&S survey, personal protective equip. |
| months | 12 | $ 54 | $ - | $ 648 | $ - | $ 648 | | On-site sanitation (rental) |
| EA | 260 | $ - | $ 25 | $ - | $ 6,500 | $ 6,500 | | S/H of samples (5 shipments per week) |
| | | | | | | | **$ 16,644** | Total Other (non-process related) |

**$ 3,739,253 TOTAL O&M (year 1)**

## OTHER TECHNOLGOY SPECIFIC COSTS (hypothetical full-scale system)

**Disposal of Hazardeous Waste**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 16,500 | $ - | $ 16,500 | $ 16,500 | | | Off-site disposal of drill cuttings |
| months | 12 | $ - | $ 250 | $ - | $ 3,000 | $ 3,000 | | | Off-site disposal of liquid wastes |
| | | | | | | | **$ 19,500** | | **Total Disposal of Hazardeous Waste** |

**$ 19,500 TOTAL OTHER TECHNOL. SPECIFIC COSTS (year 1)**

### Cyclodextrin Enhanced Flushing at a hypothetical site

Treatment approach: **Line-drive (I/E) with no UF (Year 2)**

## CAPITAL COST (hypothetical full-scale system)

No capital (fxed) cost after year 1

## 2nd Year OPERATING AND MAINTENANCE COST (hypothetical full-scale system)

**Labor**

Assume: 1 person, 8 hrs/day, 7 days/week,SCADA technology is used

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| hrs | 210 | $ 30 | $ - | $ 6,300 | $ - | $ 6,300 | | Operating labor |
| hrs | 840 | $ 30 | $ - | $ 25,200 | $ - | $ 25,200 | | Monitoring labor |
| hrs | 336 | $ 90 | $ - | $ 30,240 | $ - | $ 30,240 | | Supervision |
| | | | | | | | **$ 61,740** | **Total Labor Cost** |

**Materials**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| LB | 1038851.6 | $ - | $ 2.00 | $ - | $ 2,077,703 | $ 2,077,703 | | Cyclodextrin, tech grade |
| months | 7 | $ - | $ 500 | $ - | $ 3,500 | $ 3,500 | | H&S survey, personal protective equip. |
| month | 7 | $ - | $ 1,000 | $ - | $ 7,000 | $ 7,000 | | Consumable supplies, repairs |
| | | | | | | | **$ 2,088,203** | **Total Material Cost** |

**Utilities and Fuel**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| KWH | 33100 | $ - | $ 0.05725 | $ - | $ 1,895 | $ 1,895 | | Electricity cost |
| 1000 gal | 308 | $ - | $ 0.44 | $ - | $ 136 | $ 136 | | Water |
| | | | | | | | **$ 2,031** | **Total Utilities and Fuel Cost** |

**Equipment Ownership and Rental**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| months | 7 | $ - | $ 8,490 | $ - | $ 59,427 | $ 59,427 | | Air activated carbon filter system |
| | | | | | | | **$ 59,427** | **Total Equipment Ownership and Rental Cost** |

**Performance Testing and Analysis**

***Analysis Cost - off-site***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 28 | | $ 85 | $ - | $ 2,380 | $ 2,380 | | VOC analysis (short list) |
| | | | | | | | **$ 2,380** | **Total Performance Testing and Analysis - off site** |

***Analysis Cost - on-site***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 56 | | $ 15 | $ - | $ 840 | $ 840 | | CD analysis (TOC method) |
| EA | 28 | | $ 60 | $ - | $ 1,680 | $ 1,680 | | Field parameters (set of pH, DO, T, EC), once per week |
| | | | | | | | **$ 2,520** | **Total Performance Testing and Analysis - on site** |

**Other (non-process related)**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| hrs | 80 | | $ 125 | $ - | $ 10,000 | $ 10,000 | | Final report preparation (Project Manager) |
| EA | 140 | $ - | $ 25 | $ - | $ 3,500 | $ 3,500 | | S/H of samples (5 shipments per week) |
| months | 7 | | $ 54 | $ - | $ 378 | $ 378 | | On-site sanitation (rental) |
| | | | | | | | **$ 3,878** | Total Other (non-process related) |
| | | | | | | | **$ 2,220,178** | **TOTAL O&M (year 2)** |

## OTHER TECHNOLGOY SPECIFIC COSTS (hypothetical full-scale system)

**Disposal of Hazardeous Waste**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| months | 7 | $ - | $ 250 | $ - | $ 1,750 | $ 1,750 | | | Off-site disposal of liquid wastes |
| | | | | | | | **$ 1,750** | | **Total Disposal of Hazardeous Waste** |

**Site Restoration**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| hrs | 24 | $ 30 | | $ 720 | $ - | $ 720 | | Field crew |
| hrs | 4 | $ 90 | | $ 360 | $ - | $ 360 | | Supervision |
| | | | | | | | **$ 1,080** | **Total Site Restoration** |
| | | | | | | | **$ 2,830** | **TOTAL OTHER TECHNOL. SPECIFIC COSTS (year 2)** |

## Summary

| 2,500 ft2 Full-scale CDEF implementation<br>Line-drive (I/E) with no UF (19 Months) | | | |
|---|---|---|---|
| **Cost Category** | **Sub Category** | **Cost ($)** | |
| **FIXED COSTS** | | | |
| ***1. Capital Cost*** | Mobilization/Demobilization | $ | 10,928 |
| | Planning/Preparation | $ | 52,020 |
| | Site Investigation | $ | 101,850 |
| | Site Work | $ | 18,600 |
| | Equipment Cost - Structures | $ | - |
| | Equipment Cost - Process Equipment | $ | 66,063 |
| | Star-up and Testing | $ | 13,240 |
| | Other - Non Process Equipment | $ | 11,300 |
| | Other - Installation | $ | 119,139 |
| | Other - Engineering (1) | $ | - |
| | Other - Management Support (2) | $ | - |
| | **Sub-Total:** | **$** | **393,140** |
| **VARIABLE COSTS** | | | |
| ***2. Variable Cost*** | Labor | $ | 145,980 |
| | Materials / Consumables | $ | 5,667,980 |
| | Utilities / Fuel | $ | 15,528 |
| | Equipment Cost (A-carbon, rental) | $ | 161,301 |
| | Chemical Analysis | $ | 49,995 |
| | Other | $ | 20,522 |
| | **Sub-Total:** | **$** | **6,061,305** |
| ***3. Other Technology Specific Cost*** | Disposal of well cuttings | $ | 16,500 |
| | Disposal of liquid waste | $ | 4,750 |
| | Site Restoration | $ | 1,080 |
| | **Sub-Total:** | **$** | **22,330** |
| **TOTAL COSTS** | | | |
| | ***Total Technology Cost*** | **$** | **6,476,775** |
| | ***Quantity Treated - VOC mass (lbs)*** | | 1415 |
| | ***Unit Cost (per lbs VOC removed and treated)*** | **$** | **4,577** |

***(1) Included in planning/preparation***

***(2) Included in labor cost***

# Appendix X
## Hypothetical Full-Scale Cost System – 300 $ft^2$

### Cyclodextrin Enhanced Flushing at a hypothetical site

### CAPITAL COST (hypothetical demo-scale system)

**Assumptions**

Treatment approach: **300 ft2 - Multi-well push-pull with UF in batch mode**

| | | |
|---|---|---|
| Flushing Vol: | 9 | m3 |
| Soil mass: | 49 | tons |
| Area: | 19 | m2 |
| Project duration: | 4 | months |

Power Cons $ 0.05725
Cost / KWH
Note: Electrical power for UF is provided by generators.

Number of wells, type and depth needed for remediation

| | | |
|---|---|---|
| 6 | Injection/Extraction wells | 22.5 ft |

**DNAPL Source Zone Characterization**
Approximate extent of plume is already known

| Units | No of units | Unit labor cost (hr) | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 1,600 | $ - | $ 1,600 | $ 1,600 | | | Mob/Demob Geoprobe/Membrane Interface Probe (MIP) |
| EA | 2 | $ - | $ 3,500 | $ - | $ 7,000 | $ 7,000 | | | MIP with Electrical Conductivity |
| EA | 5 | $ 95.00 | $ - | $ 475 | $ - | $ 475 | | | Operator per diem |
| EA | 2 | $ - | $ 1,250 | $ - | $ 2,500 | $ 2,500 | | | In Situ GW/Soil sampling |
| EA | 15 | $ - | $ 126 | $ - | $ 1,890 | $ 1,890 | | | Lab Analysis (TCL Volatile Organic Compound) |
| EA | 60 | $ 50.00 | $ - | $ 3,000 | $ - | $ 3,000 | | | Labor (2 Person Field Crew) |
| EA | 3 | $ - | $ 200 | $ - | $ 600 | $ 600 | | | Equipment and Expendables |
| | | | | | | | **$ 17,065** | | **Total DNAPL Source Zone Characterization** |

**Treatability Study (Site soil testing)**

| Units | No of units | Unit labor cost (hr) | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 120 | $ 85 | $ - | $ 10,200 | $ - | $ 10,200 | | | Lab techician (soil column tests) |
| EA | 1 | $ - | $ 2,550 | $ - | $ 2,550 | $ 2,550 | | | Lab equipment |
| EA | 24 | $ 125 | | $ 3,000 | $ - | $ 3,000 | | | Report preparation |
| | | | | | | | **$ 15,750** | | **Total Cyclodextrin Selection** |

**Engineering, Design, and Modeling**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 144 | $ 125.00 | $ 1,770 | $ 18,000 | $ 1,770 | $ 19,770 | | | Work Plan, H&S plan, Site Management Plan (Project manager) |
| EA | 1 | $ - | $ 2,500 | $ - | $ 2,500 | $ 2,500 | | | Permits and licences, estimated |
| | | | | | | | **$ 22,270** | | **Total Engineering, Design, and Modeling** |

**Technology Mobilization and Demobilizatior**
Assume: Local contractors perform field work

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| hrs | 280 | $ 25 | | $ 7,000 | $ - | $ 7,000 | | | Travel to and from site (incl. accommodation) |
| EA | 2 | $ - | $ 5,464 | $ - | $ 10,928 | $ 10,928 | | | Freight (Palletizing, loading, and shipping of equipmemt) |
| | | | | | | | **$ 17,928** | | **Total Technology Mobilization and Demobilizatior** |

**Site Work**

***Site Set-up***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 1,000 | $ - | $ 1,000 | $ 1,000 | | | Secondary containment (berm) |
| EA | 1 | $ - | $ 1,450 | $ - | $ 1,400 | $ 1,400 | | | Electricity hook-up |
| EA | 80 | $ 50.00 | $ - | $ 4,000 | $ - | $ 4,000 | | | Plumbing |
| | | | | | | | **$ 6,400** | | **Total Site Set-up** |

**Installation of Equipment and Appurtenances**

***Well Field Installation***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| ft | 135 | $ - | $ 77 | $ - | $ 10,355 | $ 10,355 | | | Injection/Extraction well installation |
| EA | 6 | $ - | $ 552 | $ - | $ 3,312 | $ 3,312 | | | Grunfos submersible pumps (Model 5S) |
| EA | 1 | $ - | $ 14,800 | $ - | $ 14,800 | $ 14,800 | | | SCADA system, automated flow control |
| | | | | | | | **$ 28,467** | | **Total Well Installation** |

***Above Ground Plumbing***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| ft | 500 | $ - | $ 2 | $ - | $ 900 | $ 900 | | | Well piping, 3/4 in PVC and flex tubing |
| EA | 8 | $ - | $ 78 | $ - | $ 624 | $ 624 | | | Flowmeters |
| EA | 10 | $ - | $ 21 | $ - | $ 210 | $ 210 | | | Flow control valves |
| EA | 6 | $ - | $ 45 | $ - | $ 270 | $ 270 | | | In-line sample ports |
| EA | 3 | $ - | $ 294 | $ - | $ 882 | $ 882 | | | Transfer pumps |
| ft | 200 | $ - | $ 2 | $ - | $ 360 | $ 360 | | | Waste water disposal piping, 3/4 in flex tubing |
| ft | 60 | $ - | $ 9 | $ - | $ 516 | $ 516 | | | Connection of air stripper (6 in PVC) |
| | | | | | | | **$ 3,762** | | **Total Above Ground Piping** |
| | | | | | | | **$ 32,229** | | **Total Installation of Equipment and Appurtenances** |

**Equipment Ownership and Rental**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 10,101 | $ - | $ 10,101 | $ 10,101 | | Air stripper incl. blower (200 cfm) |
| months | 4 | $ - | $ 997 | $ - | $ 3,987 | $ 3,987 | | PID for H&S survey |
| EA | 1 | | $ 368.00 | $ - | $ 368 | $ 368 | | 250 gal mixing tank |
| | | | | | | | $ 14,456 | **Total Equipment Ownership and Rental Cost** |

**Startup and Testing**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| hrs | 48 | $ 30 | $ - | $ 1,440 | $ - | $ 1,440 | | | Operator Training (3 people field crew) |
| hrs | 144 | $ 50 | $ - | $ 7,200 | $ - | $ 7,200 | | | System shake-down, well testing, etc. |
| | | | | | | | $ 8,640 | | **Total Startup and Testing** |

**Other (non-process related)**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 4,800 | $ - | $ 4,800 | $ 4,800 | | | Office and admin. equipment (computer, printer, etc) |
| EA | 3 | $ - | $ 550 | $ - | $ 1,650 | $ 1,650 | | | H&S training (OSHA) |
| EA | 1 | $ - | $ 1,600 | $ - | $ 1,600 | $ 1,600 | | | Field safety equipment, various |
| | | | | | | | $ 8,050 | | **Total Other** |

**$ 142,787 TOTAL CAPITAL (year 1)**

## 1st Year OPERATING AND MAINTENANCE COST (hypothetical full-scale system)

**Labor**

Assume: 1 person, 8 hrs/day, 7 days/week, SCADA technology is used

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| hrs | 320 | $ 30 | $ - | $ 9,590 | $ - | $ 9,590 | | Operating labor |
| hrs | 639 | $ 30 | $ - | $ 19,181 | $ - | $ 19,181 | | Monitoring labor |
| hrs | 240 | $ 90 | $ - | $ 21,600 | $ - | $ 21,600 | | Supervision |
| | | | | | | | $ 50,371 | **Total Labor Cost** |

**Materials**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| LB | 33660 | $ - | $ 2.00 | $ - | $ 67,320 | $ 67,320 | | Cyclodextrin, tech grade |
| months | 4 | $ - | $ 500 | $ - | $ 2,000 | $ 2,000 | | H&S survey, personal protective equip. |
| month | 4 | $ - | $ 1,000 | $ - | $ 4,000 | $ 4,000 | | Consumable supplies, repairs |
| | | | | | | | $ 73,320 | **Total Material Cost** |

**Utilities and Fuel**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| KWH | 34018 | $ - | $ 0.05725 | $ - | $ 1,948 | $ 1,948 | | Electricity cost |
| gal | 3744 | $ - | $ 2.00 | $ - | $ 7,488 | $ 7,488 | | Fuel for diesel electric generator |
| 1000 gal | 176 | $ - | $ 0.44 | $ - | $ 77 | $ 77 | | Water |
| | | | | | | | $ 9,513 | **Total Utilities and Fuel Cost** |

**Equipment Ownership and Rental**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| months | 4 | $ - | $ 18,750 | $ - | $ 75,000 | $ 75,000 | | UF membrane unit for CD reconcentration |
| months | 4 | $ - | $ 1,497 | $ - | $ 5,988 | $ 5,988 | | Diesel electric generator (480 V, 22KW) |
| months | 4 | $ - | $ 832 | $ - | $ 3,328 | $ 3,328 | | Suspended solid filter system |
| months | 8 | $ - | $ 449 | $ - | $ 3,592 | $ 3,592 | | 2 x 6,500 gal holding tank |
| months | 4 | $ - | $ 5,660 | $ - | $ 22,639 | $ 22,639 | | Air activated carbon filter system |
| | | | | | | | $ 110,547 | **Total Equipment Ownership and Rental Cost** |

**Performance Testing and Analysis**

***Analysis Cost - off-site***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 48 | $ - | $ 85 | $ - | $ 4,080 | $ 4,080 | | VOC analysis (short list) |
| | | | | | | | $ 4,080 | **Total Performance Testing and Analysis - off site** |

***Analysis Cost - on-site***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 96 | $ 15 | $ - | $ 1,440 | $ - | $ 1,440 | | CD analysis (TOC method) |
| EA | 16 | $ - | $ 60 | $ - | $ 960 | $ 960 | | Field parameters (set of pH, DO, T, EC), once per week |
| | | | | | | | $ 2,400 | **Total Performance Testing and Analysis - on site** |

**Other (non-process related)**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| hrs | 64 | $ - | $ 125 | $ - | $ 8,000 | $ 8,000 | | Final report preparation (Project Manager) |
| months | 4 | $ - | $ 54 | $ - | $ 216 | $ 216 | | On-site sanitation (rental) |
| EA | 20 | $ - | $ 25 | $ - | $ 500 | $ 500 | | S/H of samples (5 shipments per week) |
| | | | | | | | $ 8,716 | Total Other (non-process related) |

**$ 148,400 TOTAL O&M (year 1)**

**OTHER TECHNOLGOY SPECIFIC COSTS (hypothetical full-scale system)**

**Disposal of Hazardeous Waste**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 3,900 | $ - | $ 3,900 | $ 3,900 | | | Off-site disposal of drill cuttings |
| months | 4 | $ - | $ 250 | $ - | $ 1,000 | $ 1,000 | | | Off-site disposal of liquid wastes |
| | | | | | | | **$ 4,900** | **Total Disposal of Hazardeous Waste** | |

**Site Restoration**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| hrs | 24 | $ 30 | | $ 720 | $ - | $ 720 | | Field crew |
| hrs | 4 | $ 90 | | $ 360 | $ - | $ 360 | | Supervision |
| | | | | | | | **$ 1,080** | **Total Site Restoration** |
| | | | | | | | **$ 5,980** | **TOTAL OTHER TECHNOL. SPECIFIC COSTS (year 1)** |

## Summary

| **300 ft2 scale CDEF implementation<br>Multi-well push-pull with UF in batch mode (4 months)** | | |
|---|---|---|
| **Cost Category** | **Sub Category** | **Cost ($)** |
| | **FIXED COSTS** | |
| ***1. Capital Cost*** | Mobilization/Demobilization | $ 17,928 |
| | Planning/Preparation | $ 38,020 |
| | Site Investigation | $ 17,065 |
| | Site Work | $ 6,400 |
| | Equipment Cost - Structures | $ - |
| | Equipment Cost - Process Equipment | $ 14,456 |
| | Star-up and Testing | $ 8,640 |
| | Other - Non Process Equipment | $ 8,050 |
| | Other - Installation | $ 32,229 |
| | Other - Engineering (1) | $ - |
| | Other - Management Support (2) | $ - |
| | **Sub-Total:** | **$ 142,787** |
| | **VARIABLE COSTS** | |
| ***2. Variable Cost*** | Labor | $ 50,371 |
| | Materials / Consumables | $ 73,320 |
| | Utilities / Fuel | $ 9,513 |
| | Equipment Cost (rental) | $ 110,547 |
| | Chemical Analysis | $ 6,480 |
| | Other | $ 8,716 |
| | **Sub-Total:** | **$ 258,947** |
| ***3. Other Technology Specific Cost*** | Disposal of well cuttings | $ 3,900 |
| | Disposal of liquid waste | $ 1,000 |
| | Site Restoration | $ 1,080 |
| | **Sub-Total:** | **$ 5,980** |
| | **TOTAL COSTS** | |
| | ***Total Technology Cost*** | **$ 407,714** |
| | ***Quantity Treated - VOC mass*** | 105 |
| | ***Unit Cost*** | **$ 3,883** |

***(1) Included in planning/preparation***
***(2) Included in labor cost***

## Cyclodextrin Enhanced Flushing at a hypothetical site

## CAPITAL COST (hypothetical full-scale system)

**Assumptions**

Treatment approach: **300 ft2 Mulit-well push-pull with UF in continuous mode**

| | | | | |
|---|---|---|---|---|
| Flushing Vol: | 9 | m3 | Power Consum $ | 0.05725 |
| Soil mass: | 49 | tons | Cost / KWH | |
| Area: | 19 | m2 | Note: Electrical power for UF is provided by generators. | |
| Project duration: | 4 | months | | |

Number of wells, type and depth needed for remediation

| | | |
|---|---|---|
| 6 | Injection/Extraction wells | 22.5 ft |

**DNAPL Source Zone Characterization**

Assume: approximate extent of plume is already known

| Units | No of units | Unit labor cost (hr) | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 1,600 | $ - | $ 1,600 | $ 1,600 | | | Mob/Demob Geoprobe/Membrane Interface Probe (MIP) |
| EA | 2 | $ - | $ 3,500 | $ - | $ 7,000 | $ 7,000 | | | MIP with Electrical Conductivity |
| EA | 5 | $ 95.00 | $ - | $ 475 | $ - | $ 475 | | | Operator per diem |
| EA | 2 | $ - | $ 1,250 | $ - | $ 2,500 | $ 2,500 | | | In Situ GW/Soil sampling |
| EA | 15 | $ - | $ 126 | $ - | $ 1,890 | $ 1,890 | | | Lab Analysis (TCL Volatile Organic Compound) |
| EA | 60 | $ 50.00 | $ - | $ 3,000 | $ - | $ 3,000 | | | Labor (2 Person Field Crew) |
| EA | 3 | $ - | $ 200 | $ - | $ 600 | $ 600 | | | Equipment and Expendables |
| | | | | | | | $ 17,065 | | **Total DNAPL Source Zone Characterization** |

**Treatability Study (Site soil testing)**

| Units | No of units | Unit labor cost (hr) | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 120 | $ 85 | $ - | $ 10,200 | $ - | $ 10,200 | | | Lab techician (soil column tests) |
| EA | 1 | $ - | $ 2,550 | $ - | $ 2,550 | $ 2,550 | | | Lab equipment |
| EA | 24 | $ 125 | | $ 3,000 | $ - | $ 3,000 | | | Report preparation |
| | | | | | | | $ 15,750 | | **Total Cyclodextrin Selection** |

**Engineering, Design, and Modeling**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 144 | $ 125.00 | $ 1,770 | $ 18,000 | $ 1,770 | $ 19,770 | | | Work Plan, H&S plan, Site Management Plan (Project manager) |
| EA | 1 | $ - | $ 2,500 | $ - | $ 2,500 | $ 2,500 | | | Permits and licences, estimated |
| | | | | | | | $ 22,270 | | **Total Engineering, Design, and Modeling** |

**Technology Mobilization and Demobilizatior**

Assume: Local contractors perform field work

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| hrs | 280 | $ 25 | | $ 7,000 | $ - | $ 7,000 | | | Travel to and from site (incl. accommodation) |
| EA | 2 | $ - | $ 5,464 | $ - | $ 10,928 | $ 10,928 | | | Freight (Palletizing, loading, and shipping of equipmemt) |
| | | | | | | | $ 17,928 | | **Tota Technology Mobilization and Demobilizatior** |

**Site Work**

***Site Set-up***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 1,000 | $ - | $ 1,000 | $ 1,000 | | | Secondary containment (berm) |
| EA | 1 | $ - | $ 1,450 | $ - | $ 1,400 | $ 1,400 | | | Electricity hook-up |
| EA | 80 | $ 50.00 | $ - | $ 4,000 | $ - | $ 4,000 | | | Plumbing |
| | | | | | | | $ 6,400 | | **Total Site Set-up** |

**Installation of Equipment and Appurtenances**

***Well Field Installation***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| ft | 135 | $ - | $ 77 | $ - | $ 10,355 | $ 10,355 | | | Injection/Extraction well installation |
| EA | 6 | $ - | $ 552 | $ - | $ 3,312 | $ 3,312 | | | Grunfos submersible pumps (Model 5S) |
| EA | 1 | $ - | $ 14,800 | $ - | $ 14,800 | $ 14,800 | | | SCADA system, automated flow control |
| | | | | | | | $ 28,467 | | **Total Well Installation** |

***Above Ground Plumbing***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| ft | 500 | $ - | $ 2 | $ - | $ 900 | $ 900 | | | Well piping, 3/4 in PVC and flex tubing |
| EA | 8 | $ - | $ 78 | $ - | $ 624 | $ 624 | | | Flowmeters |
| EA | 10 | $ - | $ 21 | $ - | $ 210 | $ 210 | | | Flow control valves |
| EA | 6 | $ - | $ 45 | $ - | $ 270 | $ 270 | | | In-line sample ports |
| EA | 3 | $ - | $ 294 | $ - | $ 882 | $ 882 | | | Transfer pumps |
| ft | 200 | $ - | $ 2 | $ - | $ 360 | $ 360 | | | Waste water disposal piping, 3/4 in flex tubing |
| ft | 60 | $ - | $ 9 | $ - | $ 516 | $ 516 | | | Connection of air stripper (6 in PVC) |
| | | | | | | | $ 3,762 | | **Total Above Ground Piping** |
| | | | | | | | $ 32,229 | | **Total Installation of Equipment and Appurtenances** |

**Equipment Ownership and Rental**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 15,152 | $ - | $ 15,152 | $ 15,152 | | Air stripper incl. blower |
| EA | 1 | | $ 368.00 | $ - | $ 368 | $ 368 | | 250 gal mixing tank |
| | | | | | | | $ 15,520 | **Total Equipment Ownership and Rental Cost** |

**Startup and Testing**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| hrs | 48 | $ 30 | $ - | $ 1,440 | $ - | $ 1,440 | | | Operator Training (6 people field crew) |
| hrs | 144 | $ 50 | $ - | $ 7,200 | $ - | $ 7,200 | | | System shake-down, well testing, etc. |
| | | | | | | | $ 8,640 | | **Total Startup and Testing** |

**Other (non-process related)**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 4,800 | $ - | $ 4,800 | $ 4,800 | | | Office and admin. equipment (computer, printer, etc) |
| EA | 3 | $ - | $ 550 | $ - | $ 1,650 | $ 1,650 | | | H&S training (OSHA) |
| EA | 1 | $ - | $ 1,600 | $ - | $ 1,600 | $ 1,600 | | | Field safety equipment, various |
| | | | | | | | $ 8,050 | | **Total Other** |

**$ 143,851 TOTAL CAPITAL (year 1)**

## 1st Year OPERATING AND MAINTENANCE COST (hypothetical full-scale system)

**Labor**

Assume: 1 person, 8 hrs/day, 7 days/week, SCADA technology is used

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| hrs | 120 | $ 30 | $ - | $ 3,596 | $ - | $ 3,596 | | Operating labor |
| hrs | 240 | $ 30 | $ - | $ 7,193 | $ - | $ 7,193 | | Monitoring labor |
| hrs | 96 | $ 90 | $ - | $ 8,640 | $ - | $ 8,640 | | Supervision |
| | | | | | | | $ 19,429 | **Total Labor Cost** |

**Materials**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| LB | 74140 | $ - | $ 2.00 | $ - | $ 148,280 | $ 148,280 | | Cyclodextrin, tech grade |
| months | 2 | $ - | $ 500 | $ - | $ 1,000 | $ 1,000 | | H&S survey, personal protective equip. |
| month | 2 | $ - | $ 1,000 | $ - | $ 2,000 | $ 2,000 | | Consumable supplies, repairs |
| | | | | | | | $ 151,280 | **Total Material Cost** |

**Utilities and Fuel**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| KWH | 17009 | $ - | $ 0.05725 | $ - | $ 974 | $ 974 | | Electricity cost |
| gal | 1872 | $ - | $ 2.00 | $ - | $ 3,744 | $ 3,744 | | Fuel for diesel electric generator |
| 1000 gal | 88 | $ - | $ 0.44 | $ - | $ 39 | $ 39 | | Water |
| | | | | | | | $ 4,756 | **Total Utilities and Fuel Cost** |

**Equipment Ownership and Rental**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| months | 2 | $ - | $ 18,750 | $ - | $ 37,500 | $ 37,500 | | UF membrane unit for CD reconcentration |
| months | 2 | $ - | $ 1,497 | $ - | $ 2,994 | $ 2,994 | | Diesel electric generator (480 V, 22KW) |
| months | 2 | $ - | $ 997 | $ - | $ 1,993 | $ 1,993 | | PID for H&S survey |
| months | 2 | $ - | $ 832 | $ - | $ 1,664 | $ 1,664 | | Suspended solid filter system |
| months | 4 | $ - | $ 449 | $ - | $ 1,796 | $ 1,796 | | 21,000 gal holding tank |
| months | 2 | $ - | $ 5,660 | $ - | $ 11,319 | $ 11,319 | | Air activated carbon filter system |
| | | | | | | | $ 57,267 | **Total Equipment Ownership and Rental Cost** |

**Performance Testing and Analysis**

***Analysis Cost - off-site***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 60 | $ - | $ 85 | $ - | $ 5,100 | $ 5,100 | | VOC analysis (short list) |
| | | | | | | | $ 5,100 | **Total Performance Testing and Analysis - off site** |

***Analysis Cost - on-site***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 120 | $ 15 | $ - | $ 1,800 | $ - | $ 1,800 | | CD analysis (TOC method) |
| EA | 8 | $ - | $ 60 | $ - | $ 480 | $ 480 | | Field parameters (set of pH, DO, T, EC), once per week |
| | | | | | | | $ 2,280 | **Total Performance Testing and Analysis - on site** |

**Other (non-process related)**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| hrs | 64 | $ - | $ 125 | $ - | $ 8,000 | $ 8,000 | | Final report preparation (Project Manager) |
| months | 2 | $ - | $ 54 | $ - | $ 108 | $ 108 | | On-site sanitation (rental) |
| EA | 10 | $ - | $ 25 | $ - | $ 250 | $ 250 | | S/H of samples (5 shipments per week) |
| | | | | | | | $ 8,358 | Total Other (non-process related) |

**$ 191,204 TOTAL O&M (year 1)**

**OTHER TECHNOLGOY SPECIFIC COSTS (hypothetical full-scale system)**

**Disposal of Hazardeous Waste**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 3,900 | $ - | $ 3,900 | $ 3,900 | | | Off-site disposal of drill cuttings |
| months | 2 | $ - | $ 250 | $ - | $ 500 | $ 500 | | | Off-site disposal of liquid wastes |
| | | | | | | | **$ 4,400** | **Total Disposal of Hazardeous Waste** | |

**Site Restoration**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| hrs | 24 | $ 30 | | $ 720 | $ - | $ 720 | | Field crew |
| hrs | 4 | $ 90 | | $ 360 | $ - | $ 360 | | Supervision |
| | | | | | | | **$ 1,080** | **Total Site Restoration** |
| | | | | | | | **$ 5,480** | **TOTAL OTHER TECHNOL. SPECIFIC COSTS (year 1)** |

# Summary

| **300 ft2 scale CDEF implementation<br>Multi-well push-pull with UF in continuous mode (2 months)** | | |
|---|---|---|
| **Cost Category** | **Sub Category** | **Cost ($)** |
| | **FIXED COSTS** | |
| ***1. Capital Cost*** | Mobilization/Demobilization | $ 17,928 |
| | Planning/Preparation | $ 38,020 |
| | Site Investigation | $ 17,065 |
| | Site Work | $ 6,400 |
| | Equipment Cost - Structures | $ - |
| | Equipment Cost - Process Equipment | $ 15,520 |
| | Star-up and Testing | $ 8,640 |
| | Other - Non Process Equipment | $ 8,050 |
| | Other - Installation | $ 32,229 |
| | Other - Engineering (1) | $ - |
| | Other - Management Support (2) | $ - |
| | **Sub-Total:** | **$ 143,851** |
| | **VARIABLE COSTS** | |
| ***2. Variable Cost*** | Labor | $ 19,429 |
| | Materials / Consumables | $ 151,280 |
| | Utilities / Fuel | $ 4,756 |
| | Equipment Cost (rental) | $ 57,267 |
| | Chemical Analysis | $ 7,380 |
| | Other | $ 8,358 |
| | **Sub-Total:** | **$ 248,470** |
| ***3. Other Technology Specific Cost*** | Disposal of well cuttings | $ 3,900 |
| | Disposal of liquid waste | $ 500 |
| | Site Restoration | $ 1,080 |
| | **Sub-Total:** | **$ 5,480** |
| | **TOTAL COSTS** | |
| | ***Total Technology Cost*** | **$ 397,801** |
| | ***Quantity Treated - VOC mass (lbs)*** | 105 |
| | ***Unit Cost (per lbs VOC removed and treated)*** | **$ 3,789** |

***(1) Included in planning/preparation***
***(2) Included in labor cost***

## Cyclodextrin Enhanced Flushing at a hypothetical site

## CAPITAL COST (hypothetical demo-scale system)

### Assumptions

Treatment approach: **300 ft2 Line-drive (I/E) with UF in continous mode**

| | | |
|---|---|---|
| Flushing Vol: | 9 | m3 |
| Soil mass: | 49 | tons |
| Area: | 19 | m2 |
| Project duration: | 2 | months |

Power Consumption in: KW
Cost / KWH $ 0.05725
Note: Electrical power for UF is provided by generator.

Number of wells, type and depth needed for remediation

| | | |
|---|---|---|
| 3 | Injection wells | 22.5 ft |
| 3 | Extraction wells | 22.5 ft |
| 2 | Hydraulic control wells | 22.5 ft |

### DNAPL Source Zone Characterization

Assume: approximate extent of plume is already known

| Units | No of units | Unit labor cost (hr) | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 1,600 | $ - | $ 1,600 | $ 1,600 | | | Mob/Demob Geoprobe/Membrane Interface Probe (MIP) |
| EA | 2 | $ - | $ 3,500 | $ - | $ 7,000 | $ 7,000 | | | MIP with Electrical Conductivity |
| EA | 5 | $ 95.00 | $ - | $ 475 | $ - | $ 475 | | | Operator per diem |
| EA | 2 | $ - | $ 1,250 | $ - | $ 2,500 | $ 2,500 | | | In Situ GW/Soil sampling |
| EA | 15 | $ - | $ 126 | $ - | $ 1,890 | $ 1,890 | | | Lab Analysis (TCL Volatile Organic Compound) |
| EA | 60 | $ 50.00 | $ - | $ 3,000 | $ - | $ 3,000 | | | Labor (2 Person Field Crew) |
| EA | 3 | $ - | $ 200 | $ - | $ 600 | $ 600 | | | Equipment and Expendables |
| | | | | | | | $ 17,065 | | **Total DNAPL Source Zone Characterization** |

### Treatability Study (Site soil testing)

| Units | No of units | Unit labor cost (hr) | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 120 | $ 85 | $ - | $ 10,200 | $ - | $ 10,200 | | | Lab techician (soil column tests) |
| EA | 1 | $ - | $ 2,550 | $ - | $ 2,550 | $ 2,550 | | | Lab equipment |
| EA | 24 | $ 125 | | $ 3,000 | $ - | $ 3,000 | | | Report preparation |
| | | | | | | | $ 15,750 | | **Total Cyclodextrin Selection** |

### Engineering, Design, and Modeling

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 144 | $ 125.00 | $ 1,770 | $ 18,000 | $ 1,770 | $ 19,770 | | | Work Plan, H&S plan, Site Management Plan (Project manager) |
| EA | 1 | $ - | $ 2,500 | $ - | $ 2,500 | $ 2,500 | | | Permits and licences, estimated |
| | | | | | | | $ 22,270 | | **Total Engineering, Design, and Modeling** |

### Technology Mobilization and Demobilizatior

Assume: Local contractors perform field work

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| hrs | 280 | $ 25 | | $ 7,000 | $ - | $ 7,000 | | | Travel to and from site (incl. accommodation) |
| EA | 2 | $ - | $ 5,464 | $ - | $ 10,928 | $ 10,928 | | | Freight (Palletizing, loading, and shipping of equipmemt) |
| | | | | | | | $ 17,928 | | **Total Technology Mobilization and Demobilizatior** |

### Site Work

*Site Set-up*

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 1,000 | $ - | $ 1,000 | $ 1,000 | | | Secondary containment (berm) |
| EA | 1 | $ - | $ 1,450 | $ - | $ 1,400 | $ 1,400 | | | Electricity hook-up |
| EA | 80 | $ 50.00 | $ - | $ 4,000 | $ - | $ 4,000 | | | Plumbing |
| | | | | | | | $ 6,400 | | **Total Site Set-up** |

### Installation of Equipment and Appurtenances

*Well Field Installation*

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| ft | 180 | $ - | $ 77 | $ - | $ 13,806 | $ 13,806 | | | Injection/Extraction well installation |
| EA | 8 | $ - | $ 552 | $ - | $ 4,416 | $ 4,416 | | | Grunfos submersible pumps (Model 5S) |
| EA | 1 | $ - | $ 14,800 | $ - | $ 14,800 | $ 14,800 | | | SCADA system, automated flow control |
| | | | | | | | $ 33,022 | | **Total Well Installation** |

*Above Ground Plumbing*

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| ft | 500 | $ - | $ 2 | $ - | $ 900 | $ 900 | | | Well piping, 3/4 in PVC and flex tubing |
| EA | 8 | $ - | $ 78 | $ - | $ 624 | $ 624 | | | Flowmeters |
| EA | 10 | $ - | $ 21 | $ - | $ 210 | $ 210 | | | Flow control valves |
| EA | 6 | $ - | $ 45 | $ - | $ 270 | $ 270 | | | In-line sample ports |
| EA | 3 | $ - | $ 294 | $ - | $ 882 | $ 882 | | | Transfer pumps |
| ft | 200 | $ - | $ 2 | $ - | $ 360 | $ 360 | | | Waste water disposal piping, 3/4 in flex tubing |
| ft | 60 | $ - | $ 9 | $ - | $ 516 | $ 516 | | | Connection of air stripper (6 in PVC) |
| | | | | | | | $ 3,762 | | **Total Above Ground Piping** |
| | | | | | | | $ 36,784 | | **Total Installation of Equipment and Appurtenances** |

**Equipment Ownership and Rental**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 10,101 | $ - | $ 10,101 | $ 10,101 | | Air stripper incl. blower (200 cfm) |
| months | 4 | $ - | $ 997 | $ - | $ 3,987 | $ 3,987 | | PID for H&S survey |
| EA | 1 | | $ 368.00 | $ - | $ 368 | $ 368 | | 250 gal mixing tank |
| | | | | | | | $ 14,456 | **Total Equipment Ownership and Rental Cost** |

**Startup and Testing**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| hrs | 48 | $ 30 | $ - | $ 1,440 | $ - | $ 1,440 | | | Operator Training (6 people field crew) |
| hrs | 144 | $ 50 | $ - | $ 7,200 | $ - | $ 7,200 | | | System shake-down, well testing, etc. |
| | | | | | | | $ 8,640 | | **Total Startup and Testing** |

**Other (non-process related)**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 4,800 | $ - | $ 4,800 | $ 4,800 | | | Office and admin. equipment (computer, printer, etc) |
| EA | 3 | $ - | $ 550 | $ - | $ 1,650 | $ 1,650 | | | H&S training (OSHA) |
| EA | 1 | $ - | $ 1,600 | $ - | $ 1,600 | $ 1,600 | | | Field safety equipment, various |
| | | | | | | | $ 8,050 | | **Total Other** |

**$ 147,343 TOTAL CAPITAL (year 1)**

## 1st Year OPERATING AND MAINTENANCE COST (hypothetical full-scale system)

**Labor**

Assume: 1 person, 8 hrs/day, 7 days/week, SCADA technology is used

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| hrs | 160 | $ 30 | $ - | $ 4,795 | $ - | $ 4,795 | | Operating labor |
| hrs | 320 | $ 30 | $ - | $ 9,590 | $ - | $ 9,590 | | Monitoring labor |
| hrs | 96 | $ 90 | $ - | $ 8,640 | $ - | $ 8,640 | | Supervision |
| | | | | | | | $ 23,026 | **Total Labor Cost** |

**Materials**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| LB | 233200 | $ - | $ 2.00 | $ - | $ 466,400 | $ 466,400 | | Cyclodextrin, tech grade |
| months | 2 | $ - | $ 500 | $ - | $ 1,000 | $ 1,000 | | H&S survey, personal protective equip. |
| month | 2 | $ - | $ 1,000 | $ - | $ 2,000 | $ 2,000 | | Consumable supplies, repairs |
| | | | | | | | $ 469,400 | **Total Material Cost** |

**Utilities and Fuel**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| KWH | 18089 | $ - | $ 0.05725 | $ - | $ 1,036 | $ 1,036 | | Electricity cost |
| gal | 1872 | $ - | $ 2.00 | $ - | $ 3,744 | $ 3,744 | | Fuel for diesel electric generator |
| 1000 gal | 88 | $ - | $ 0.44 | $ - | $ 39 | $ 39 | | Water |
| | | | | | | | $ 4,818 | **Total Utilities and Fuel Cost** |

**Equipment Ownership and Rental**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| months | 2 | $ - | $ 18,750 | $ - | $ 37,500 | $ 37,500 | | UF membrane unit for CD reconcentration |
| months | 2 | $ - | $ 1,497 | $ - | $ 2,994 | $ 2,994 | | Diesel electric generator (480 V, 22KW) |
| months | 2 | $ - | $ 832 | $ - | $ 1,664 | $ 1,664 | | Suspended solid filter system |
| months | 4 | $ - | $ 449 | $ - | $ 1,796 | $ 1,796 | | 2 x 6,500 gal holding tank |
| months | 2 | $ - | $ 5,660 | $ - | $ 11,319 | $ 11,319 | | Air activated carbon filter system |
| | | | | | | | $ 55,273 | **Total Equipment Ownership and Rental Cost** |

**Performance Testing and Analysis**

***Analysis Cost - off-site***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 60 | | $ 85 | $ - | $ 5,100 | $ 5,100 | | VOC analysis (short list) |
| | | | | | | | $ 5,100 | **Total Performance Testing and Analysis - off site** |

***Analysis Cost - on-site***

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| EA | 120 | | $ 15 | $ - | $ 1,800 | $ 1,800 | | CD analysis (TOC method) |
| EA | 8 | | $ 60 | $ - | $ 480 | $ 480 | | Field parameters (set of pH, DO, T, EC), once per week |
| | | | | | | | $ 2,280 | **Total Performance Testing and Analysis - on site** |

**Other (non-process related)**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| hrs | 64 | $ - | $ 125 | $ - | $ 8,000 | $ 8,000 | | Final report preparation (Project Manager) |
| months | 4 | $ - | $ 54 | $ - | $ 216 | $ 216 | | On-site sanitation (rental) |
| EA | 20 | $ - | $ 25 | $ - | $ 500 | $ 500 | | S/H of samples (5 shipments per week) |
| | | | | | | | $ 8,716 | Total Other (non-process related) |

**$ 513,340 TOTAL O&M (year 1)**

**OTHER TECHNOLGOY SPECIFIC COSTS (hypothetical full-scale system)**

**Disposal of Hazardeous Waste**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Power consumption | Item description |
|---|---|---|---|---|---|---|---|---|---|
| EA | 1 | $ - | $ 3,900 | $ - | $ 3,900 | $ 3,900 | | | Off-site disposal of drill cuttings |
| months | 2 | $ - | $ 250 | $ - | $ 500 | $ 500 | | | Off-site disposal of liquid wastes |
| | | | | | | | **$ 4,400** | | **Total Disposal of Hazardeous Waste** |

**Site Restoration**

| Units | No of units | Unit labor cost | Unit mat cost | Labor cost | Mat cost | Item cost | Total cost | Item description |
|---|---|---|---|---|---|---|---|---|
| hrs | 24 | $ 30 | | $ 720 | $ - | $ 720 | | Field crew |
| hrs | 4 | $ 90 | | $ 360 | $ - | $ 360 | | Supervision |
| | | | | | | | **$ 1,080** | **Total Site Restoration** |
| | | | | | | | **$ 5,480** | **TOTAL OTHER TECHNOL. SPECIFIC COSTS (year 1)** |

# Summary

| **300 ft2 scale CDEF implementation<br>Line-drive (I/E) with UF in continous mode (2 months)** | | |
|---|---|---|
| **Cost Category** | **Sub Category** | **Cost ($)** |
| | **FIXED COSTS** | |
| ***1. Capital Cost*** | Mobilization/Demobilization | $ 17,928 |
| | Planning/Preparation | $ 38,020 |
| | Site Investigation | $ 17,065 |
| | Site Work | $ 6,400 |
| | Equipment Cost - Structures | $ - |
| | Equipment Cost - Process Equipment | $ 14,456 |
| | Star-up and Testing | $ 8,640 |
| | Other - Non Process Equipment | $ 8,050 |
| | Other - Installation | $ 36,784 |
| | Other - Engineering (1) | $ - |
| | Other - Management Support (2) | $ - |
| | **Sub-Total:** | **$ 147,343** |
| | **VARIABLE COSTS** | |
| ***2. Variable Cost*** | Labor | $ 23,026 |
| | Materials / Consumables | $ 469,400 |
| | Utilities / Fuel | $ 4,818 |
| | Equipment Cost (A-carbon, rental) | $ 55,273 |
| | Chemical Analysis | $ 7,380 |
| | Other | $ 8,716 |
| | **Sub-Total:** | **$ 568,613** |
| ***3. Other Technology Specific Cost*** | Disposal of well cuttings | $ 3,900 |
| | Disposal of liquid waste | $ 500 |
| | Site Restoration | $ 1,080 |
| | **Sub-Total:** | **$ 5,480** |
| | **TOTAL COSTS** | |
| | ***Total Technology Cost*** | **$ 721,436** |
| | ***Quantity Treated - VOC mass (lbs)*** | 105 |
| | ***Unit Cost (per lbs VOC removed and treated)*** | **$ 6,871** |

***(1) Included in planning/preparation***
***(2) Included in labor cost***

# Appendix XI - Well Logs

University of Rhode Island
Department of Geosciences
Kingston, RI 02881

**Drill Log** **I 1**

| | |
|---|---|
| Project | ESTCP CU-0113 (Cyclodextrin Demo) |
| Location | NAB Little Creek, VA |
| Date Drilled | 6/5/2002 |

| | | | |
|---|---|---|---|
| Total Depth of Hole | 24 ft | Water level | 7 ft |
| Screen Diameter | 4 " PVC | Screen Length | 5 ft |
| Casing Diameter | -- | Screen Slot | V-Slot 20 |
| Drilling Company | Parrat&Wolff | Drilling Method | 6 1/4 Auger (hollow stem) |
| Log by | Boving | Sand bags | 5 (#2 Sand) |
| No Drums | 1 1/2 | Sampling | 2 " split spoon |

| Depth (ft) | Well Construction | PID (ppm) | Sample | Annulus | Description |
|---|---|---|---|---|---|
| 0 | | | | | Ground Surface |
| | | | | | Top soil, grass covered, dark brown, moist |
| 1 | Cap | | | | |
| 2 | | | | | Sand, gray, dry, loose (fill material) |
| 3 | | | | | Concrete pieces |
| 4 | | | | | Silt, dark brown to light brown |
| 5 | | | | | |
| 6 | | | | | |
| 7 | | | | | |
| 8 | | | | Grout | |
| 9 | Pipe | | | | |
| 10 | | | | | |
| 11 | | | | | |
| 12 | | | | | Interbedded fine, medium and coarse sand, light brown, wet at 7 ft |
| 13 | | | | | |
| 14 | | | | | |
| 15 | | | | Bent. | |
| 16 | | | | | |
| 17 | | | | | |
| 18 | | | | Sand | |
| 19 | | | | | |
| 20 | Screen | 1 | | | |
| | | 24 | | | Sandy silt, brown |
| 21 | | 44 | | | |
| | | 16 | I1-1 | | Clay, gray, shell fragments |
| 22 | | 96 | | | |
| | | 29 | | | Sand, medium, brown |
| 23 | Cap | | | | |
| | | 9.2 | I1-2 | | Clay, gray, shell fragments |
| 24 | | * | | | |
| 25 | | | | | * PID readings during drilling at well head up to 2808 ppm |

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## Drill Log E 1

| | |
|---|---|
| Project | ESTCP CU-0113 (Cyclodextrin Demo) |
| Location | NAB Little Creek, VA |
| Date Drilled | 6/4/2002 |

| | | | |
|---|---|---|---|
| Total Depth of Hole | 22 ft | Water level | 7 ft |
| Screen Diameter | 4 " PVC | Screen Length | 5 ft |
| Casing Diameter | -- | Screen Slot | V-Slot 20 |
| Drilling Company | Parrat&Wolff | Drilling Method | 6 1/4 Auger (hollow stem) |
| Log by | Blanford | Sand bags | 5 (#2 Sand) |
| No Drums | 1 4/5 | Sampling | 2" split spoon, cored every 2 ft continuously from surface |

| Depth (ft) | Well Construction | PID (ppm) | Sample | Graphic Log | | | Description |
|---|---|---|---|---|---|---|---|
| | | | | | | | Ground Surface |
| | | | | | | | Top soil, grass covered, dark brown, moist |
| 1 | Cap | | | | 1 | | |
| 2 | | | | | 2 | | |
| 3 | | | | | 3 | | Clayey silty, light brown, unsaturated |
| 4 | | | | | 4 | | |
| 5 | | | | | 5 | | |
| 6 | | | | | 6 | | |
| 7 | | | | | 7 | Grout | |
| 8 | | | | | 8 | | Interbedded fine, medium and coarse sand, light brown, wet at 7 ft |
| 9 | Pipe | | | | 9 | | |
| 10 | | | | | 10 | | |
| 11 | | | E1-1 | | 11 | | |
| 12 | | | E1-2 | | 12 | | |
| 13 | | | E1-3 | | 13 | Bent. | |
| 14 | | | E1-4 | | 14 | | |
| 15 | | | E1-5 | | 15 | | Sand, medium, brown |
| 16 | | | E1-6 | | 16 | | |
| 17 | | | E1-7 | | 17 | | |
| 18 | Screen | | E1-7 | | 18 | Sand | |
| 19 | | | E1-8 | | 19 | | |
| 20 | | | E1-9 | | 20 | | |
| 21 | | 5 | E1-10 | | 21 | | Sand, coarse |
| 22 | Cap | | E1-11 | | 22 | | Clay, gray, shell fragments |
| 23 | | | E1-12 | | 23 | | |
| 24 | | | E1-13 | | 24 | | |
| 25 | | | | | 25 | | |

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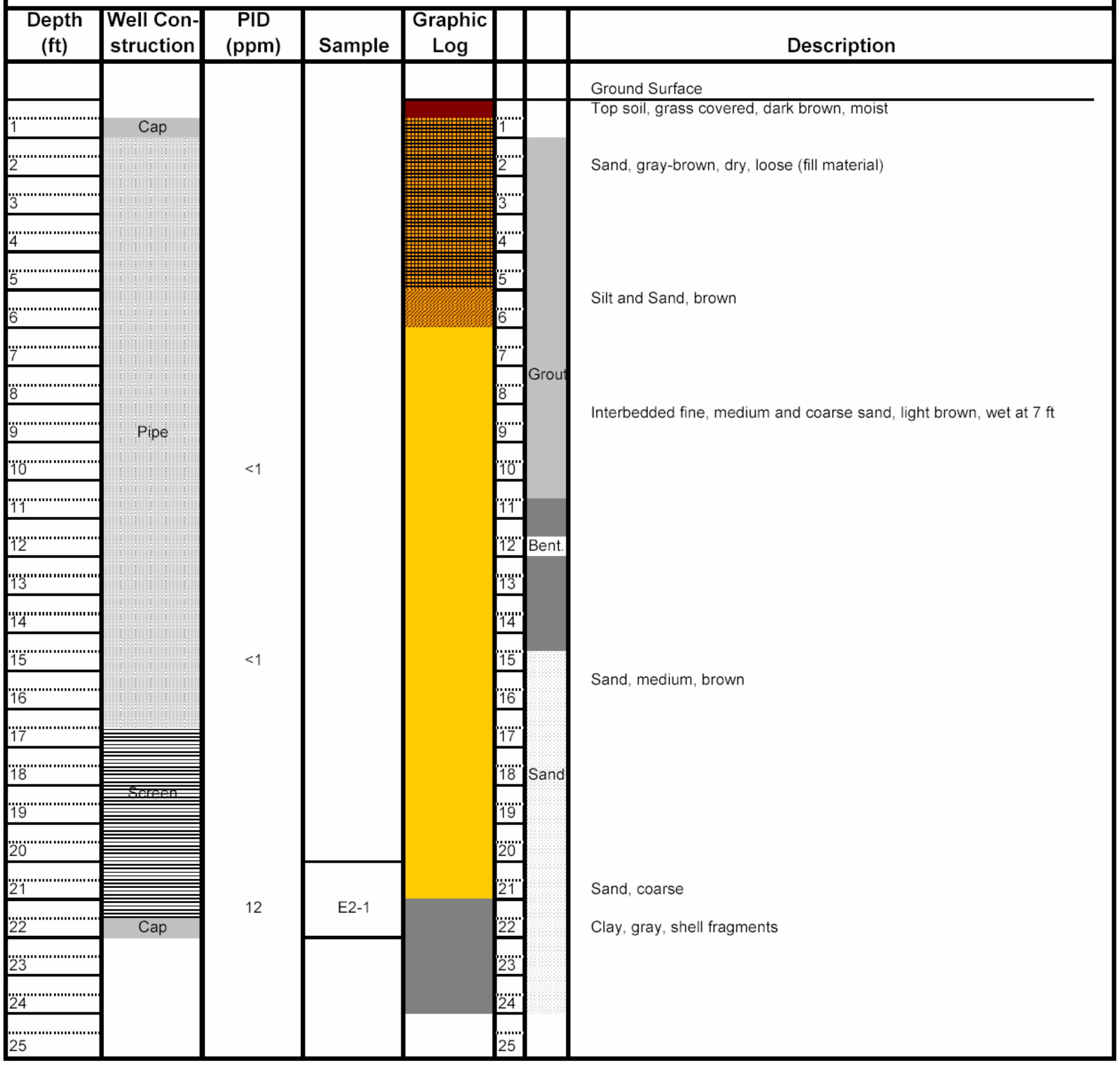
## Drill Log E 2

| | |
|---|---|
| Project | ESTCP CU-0113 (Cyclodextrin Demo) |
| Location | NAB Little Creek, VA |
| Date Drilled | 6/5/2002 |

| | | | |
|---|---|---|---|
| Total Depth of Hole | 24 ft | Water level | 7 ft |
| Screen Diameter | 4 " PVC | Screen Length | 5 ft |
| Casing Diameter | -- | Screen Slot | V-Slot 20 |
| Drilling Company | Parrat&Wolff | Drilling Method | 6 1/4 Auger (hollow stem) |
| Log by | Boving | Sand bags | 4 1/2 (#2 Sand) |
| No Drums | 1 3/4 | Sampling | 2 " split spoon |



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## Drill Log E 3

| | |
|---|---|
| Project | ESTCP CU-0113 (Cyclodextrin Demo) |
| Location | NAB Little Creek, VA |
| Date Drilled | 6/4/2002 |

| | | | |
|---|---|---|---|
| Total Depth of Hole | 23.5 ft | Water level | 7 ft |
| Screen Diameter | 4 " PVC | Screen Length | 5 ft |
| Casing Diameter | -- | Screen Slot | V-Slot 20 |
| Drilling Company | Parrat&Wolff | Drilling Method | 6 1/4 Auger (hollow stem) |
| Log by | Boving | Sand bags | 5 (#2 Sand) |
| No Drums | 1 1/2 | Sampling | 2 " split spoon |

| Depth (ft) | Well Construction | PID (ppm) | Sample | Annulus | Description |
|---|---|---|---|---|---|
| 0 | | | | | Ground Surface |
| | | | | | Top soil, grass covered, dark brown, moist |
| 1 | Cap | | | | |
| 2 | | | | | Sand, gray, dry, loose (fill material) |
| 3 | | | | | Concrete pieces |
| 4 | | | | | Clay, gray, fill |
| 5 | | | | | |
| 6 | | | | | |
| 7 | | | | Grout | |
| 8 | | | | | |
| 9 | Pipe | | | | |
| 10 | | | | | |
| 11 | | | | | Interbedded fine, medium and coarse sand, light brown, wet at 7 ft |
| 12 | | | | | |
| 13 | | | | | |
| 14 | | | | Bent. | |
| 15 | | | | | |
| 16 | | | | | |
| 17 | | | | | |
| 18 | | | | Sand | |
| 19 | | | | | |
| 20 | | 75 | | | |
| | | 90 | | | Sand, medium, brown |
| 21 | Screen | 370 | E3-1 | | Clay, gray, shell fragments |
| 22 | | | | | Sand, medium |
| 23 | | 70 | E3-2 | | Clay, gray, shell fragments |
| 24 | Cap | * | | | |
| 25 | | | | | |

* PID readings during drilling at well head up to 2615 ppm

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## Drill Log E 4

| | | | |
|---|---|---|---|
| Project | ESTCP CU-0113 (Cyclodextrin Demo) | | |
| Location | NAB Little Creek, VA | | |
| Date Drilled | 6/4/2002 | | |
| Total Depth of Hole | 22 ft | Water level | 7 ft |
| Screen Diameter | 4 " PVC | Screen Length | 5 ft |
| Casing Diameter | -- | Screen Slot | V-Slot 20 |
| Drilling Company | Parrat&Wolff | Drilling Method | 6 1/4 Auger (hollow stem) |
| Log by | Boving | Sand bags | 5 (#2 Sand) |
| No Drums | 2 | Sampling | 2" split spoon, cored every 2 ft continuously from surface |

| Depth (ft) | Well Con-struction | PID (ppm) | Sample | Annular fill | Description |
|---|---|---|---|---|---|
| 0 | | | | | Ground Surface<br>Top soil, grass covered, dark brown, moist |
| 1 | Cap | | | | |
| 2 | | | | | Sand, gray, dry, loose (fill material), concrete pieces |
| 3 | | | | | |
| 4 | | | | | Clay, gray, fill |
| 5 | | <1 | | | |
| 6 | | | | | |
| 7 | | | | Grout | |
| 8 | | | E4-1 | | Interbedded fine, medium and coarse sand, light brown, wet at 7 ft |
| 9 | Pipe | | | | |
| 10 | | <1 | | | |
| 11 | | | | | |
| 12 | | | | | |
| 13 | | | E4-2 | Bent. | |
| 14 | | | E4-3 | | |
| 15 | | <1 | | | Sand, medium, brown |
| 16 | | | E4-4 | | |
| 17 | | | E4-5 | | |
| 18 | Screen | | | Sand | |
| 19 | | | | | |
| 20 | | <1 | E4-6 | | |
| 21 | | 1.6 | | | Sand, coarse |
| 22 | Cap | | E4-7 | | Clay, gray, shell fragments |
| 23 | | | | | |
| 24 | | | | | |
| 25 | | | | | |

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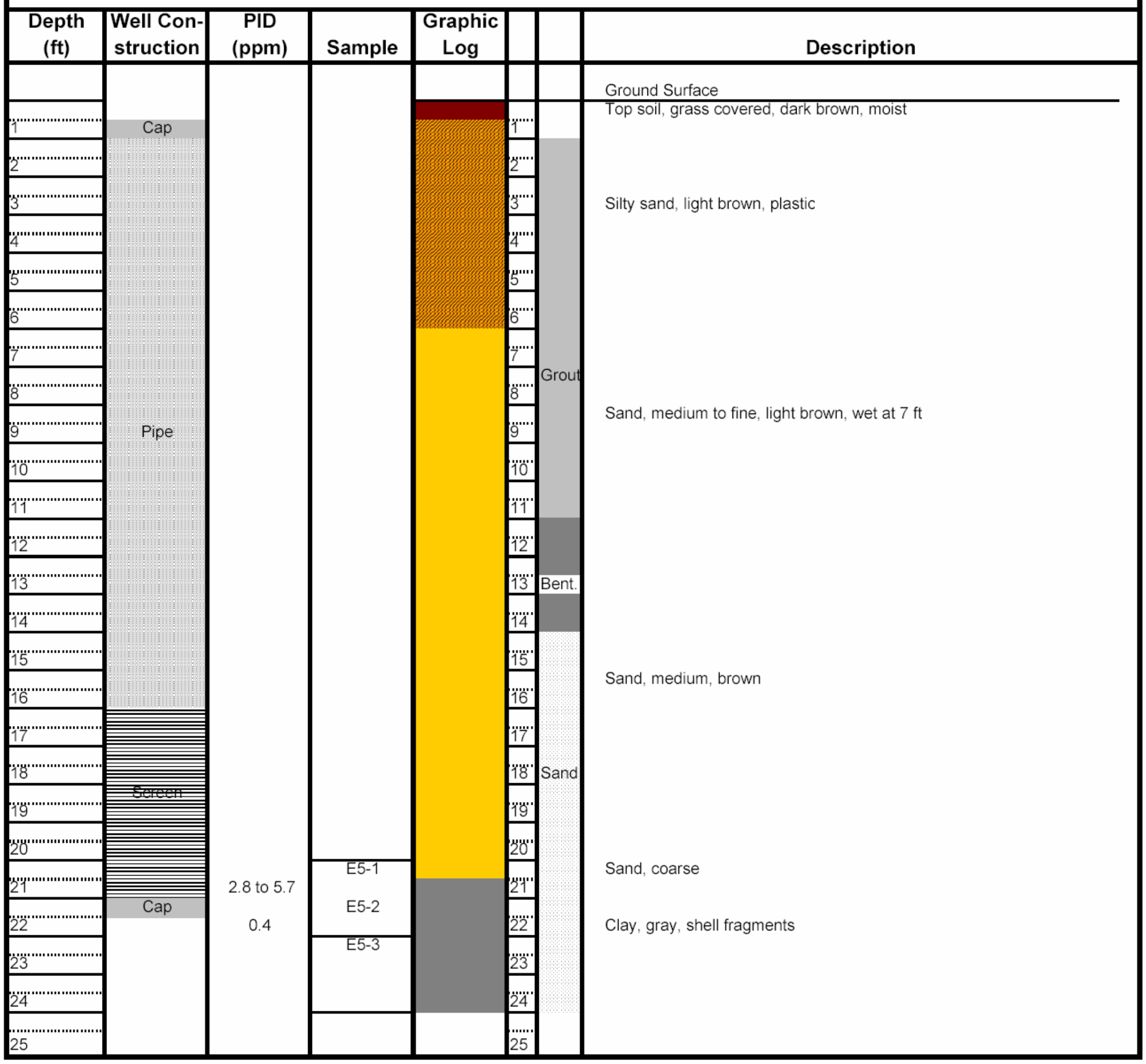
## Drill Log E 5

| | |
|---|---|
| Project | ESTCP CU-0113 (Cyclodextrin Demo) |
| Location | NAB Little Creek, VA |
| Date Drilled | 6/4/2002 |

| | | | |
|---|---|---|---|
| Total Depth of Hole | 24 ft | Water level | 7 ft |
| Screen Diameter | 4 " PVC | Screen Length | 5 ft |
| Casing Diameter | -- | Screen Slot | V-Slot 20 |
| Drilling Company | Parrat&Wolff | Drilling Method | 6 1/4 Auger (hollow stem) |
| Log by | Boving | Sand bags | 4 (#2 Sand) |
| No Drums | 2 | Sampling | 2 " split spoon |



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**Drill Log** **E 6**

| | |
|---|---|
| Project | ESTCP CU-0113 (Cyclodextrin Demo) |
| Location | NAB Little Creek, VA |
| Date Drilled | 6/5/2002 |

| | | | |
|---|---|---|---|
| Total Depth of Hole | 22 ft | Water level | 7.5 ft |
| Screen Diameter | 4 " PVC | Screen Length | 5 ft |
| Casing Diameter | -- | Screen Slot | V-Slot 20 |
| Drilling Company | Parrat&Wolff | Drilling Method | 6 1/4 Auger (hollow stem) |
| Log by | Boving | Sand bags | 5 (#2 Sand) |
| No Drums | 2 | Sampling | 2 " split spoon |