ESTCP
Cost and Performance Report

(CU-0113)

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

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ENVIRONMENTAL SECURITY
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ACRONYMS AND ABBREVIATIONS

AFB	Air Force Base
ARAR	applicable or relevant and appropriate requirements
atm	Atmospheres
bgs	below ground surface
BTC	Breakthrough Curve
c	Means of 5 initial RFs for a compound
CAA	Clean Air Act
C/Co	Relative Concentration
CD	cyclodextrin (specifically: hydroxypropyl-β-cyclodextrin)
CDEF	Cyclodextrin Enhanced Flushing
CERCLA	Comprehensive Environmental Response Compensation and Liability Act
CMC	Critical Micelle Concentration
CFR	Code of Federal Regulations
CL	Camp Lejeune
CMCD	Carboxymethyl-β-cyclodextrin
Co-PI	Co Principal Investigator
COTS	commercial off-the-shelf
CPPT	cyclodextrin push-pull test
CSM	Colorado School of Mines
CWA	Clean Water Act
DERP	Defense Environmental Restoration Program
DNAPL	dense nonaqueous 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
FFCA	Federal Facilities Compliance Act
FS	Feasibility Study
FRTR	Federal Remediation Technologies Roundtable
gpd	gallons per day
gpm	gallons per minute
GW	groundwater

HASP	Health and Safety Plan
He	Helium
HPCD	hydroxypropyl-β-cyclodextrin
HRSD	Hampton Road Sanitation District
I 1	Injection Well
IAS	Initial Assessment Study
I/E	Injection and Extraction
I/E	injection/extraction test
IPA	Isopropyl Alcohol
IRI	Interim Remedial Investigation
IRP	Installation Restoration Program
ISE	Ion Selective Electrode
K	Hydraulic Conductivity
K_{NW}	NAPL-water portioning coefficients
LANTDIV	Atlantic Division, Naval Facilities Engineering Command
LNAPL	light nonaqueous phase liquid
lpm	liters per minute
MCB	Marine Corps Base
MCL	maximum contaminant level
MIP	Membrane Interface Probe
MSDS	Materials Safety Data Sheet
MW	Monitoring Well or Molecular Weight
N	Number of calibration points (x,y data pairs)
Ne	Neon
NABLC	Naval Amphibious Base Little Creek
NACIP	Navy Assessment and Control of Installation Pollutants
NAPL	nonaqueous phase liquid
NPL	National Priorities List
NPV	net present value
NTR	Navy Technical Representative
OVM	Organic Vapor Meter
OSHA	Occupational Health and Safety Administration
PAH	polycyclic aromatic hydrocarbon
P&T	pump-and-treat
PCE	Tetrachloroethylene (tetrachloroethene)
PI	principal investigator
PID	Photoionization Detector
POTW	publicly-operated treatment works

PPB	Parts per Billion (approximately 1 µg/L)
PPM	Parts per Million (approximately 1 mg/L)
PTT	partition tracer test
PVP	pervaporation
PWC	Public Works Center
QA	Quality Assurance
QAPP	Quality Assurance Project Plan
QA/QC	Quality Assurance/Quality Control
QC	Quality Control
RAB	Restoration Advisory Board
RCRA	Resource Conservation and Recovery Act
RF	fluorescence spectrometry
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
SDWA	Safe Drinking Water Act
SEAR	surfactant enhanced aquifer remediation
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
TOC	total organic carbon
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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1.0 EXECUTIVE SUMMARY

Nonaqueous phase liquid (NAPL) spills in the subsurface are considered the single most important factor limiting remediation of military and industrial organic-contaminated sites. The generally limited performance of conventional groundwater pump-and-treat (P&T) systems has led to consideration of chemically enhanced flushing methods such as cyclodextrin enhanced flushing (CDEF). Cyclodextrins are nontoxic, modified sugars that form complexes with hydrophobic pollutants such as trichloroethylene (TCE). Because of its nontoxicity, CDEF technology is an attractive alternative to other chemical flushing agents, such as many surfactants or cosolvent formulations.

CDEF 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 P&T 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.

Funded by the Environmental Security Technology Certification Program (ESTCP), this technology demonstration was intended to show the potential of CDEF under near 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 (DNAPL) from polluted groundwater, (2) test unrefined liquid cyclodextrin (CD) as a substitute for CD powder, (3) evaluate membrane technology for recovering and reusing CD, (4) identify the most appropriate wastewater treatment technologies, and (5) conduct partition tracer test (PTT) for mass balancing.

Regulations that pertained to the implementation of this demonstration include the U.S. Environmental Protection Agency (EPA) Safe Drinking Water Act (SDWA) and its amendments under the provision of Public Law 93-523. Under these provisions, maximum contaminant levels (MCL) for dissolved volatile organic compound (VOC) (and other compounds) are established. 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 that 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."

The overall duration of the demonstration was 4 months, during which time approximately 32.5 kg TCE and 1,1,1-trichloroethane (1,1,1-TCA) plus an estimated 3 kg of 1,1-dichlorethene (1,1-DCE) and an unknown amount of other contaminants were removed. (Total DNAPL volume removed was approximately 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 VOC recoveries during the demonstration. TCE concentrations in the reference wells declined between 38.5% to 99.4% (77.3% average) from their pre-CDEF levels. The original performance objectives for this demonstration were to remove >90% of the DNAPL mass and reduce the aqueous TCE concentration to <1% of the initial TCE concentration. Neither criterion was not met during the relatively short duration of this demonstration.

A large fraction of DNAPL (approximately 57%) was removed during the PTTs because of the large volume of groundwater pumped during these tests. Based on identical extraction rates, however, about -68% more TCE was removed during the push-pull CDEF than during the PTTs. Similarly, based on operation time, about 3.5 times more TCE was removed on a daily basis during CDEF. These comparisons were based on a very conservative projection of the performance of a theoretical P&T remediation system.

The highest aqueous TCE concentrations measured during the CDEF demonstration were >200 mg/L or up to 9 times higher than the average pretreatment TCE concentrations. Even higher solubility enhancements (up to 19 times) were observed for 1,1,1-TCA. These values demonstrate clearly that CDEF significantly enhanced the contaminant removal rates.

Effluent treatment by air stripping lowered the TCE concentration in the effluent below the maximum contaminant level (MCL for TCE = 5 µg/L). Four wells that were drilled by NABLC before the CDED demonstration served as a measure of the performance of CDEF treatment. The TCE concentrations in three wells declined between 38.5% and 99.4% (77.3% average) from their preremediation levels. The TCE in concentration in one well remained essentially unchanged at approximately 1 µg/L, which is below the MCL for TCE (5 µg/L). This project was intended as a technology demonstration only — the remediation of the entire test site was not a primary objective.

Liquid, technical grade CD has been demonstrated to perform as well as 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 of reconcentrating 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 operation in-line.

A conventional air stripper and a pervaporation (PVP) system were tested. Although full-scale 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%). However, the operation of the PVP system required a system-dedicated field technician and consumed large amounts of electrical energy. In addition, the pervaporation process created a highly VOC-enriched effluent that had to be disposed of. In comparison, the air stripper was much easier to operate and required little maintenance. Also, substantially less energy was needed to run 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 (I/E) wells test and application of CDEF in multi-well push-pull mode, cyclodetrixin push-pull test (CPPT). The I/E test was conducted by injecting 20% CD solution into injection wells. After passage through the DNAPL source zone, the flushing solution was recovered from a number of extraction wells, treated, reconditioned, then reinjected. During push-pull application, a slug of 20% CD solution was injected then extracted from the same wells. The extracted flushing solution was reconditioned (i.e., the CD concentration was readjusted to 20%), then reinjected again. Up to three wells were treated in 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. The full-scale implementation of a hypothetical site — about 10 times larger than the demonstration site — generated costs comparable to other conventional or innovative remediation technologies. The main cost savings are associated with much shorter remediation times that can be realized by using CDEF instead of P&T.

The primary goal in most military and industrial remediation projects is to achieve an environmentally acceptable expedited cleanup of a site at a fixed price. The demonstration addressed these issues by demonstrating that environmentally acceptable expedited cleanup of a DNAPL site at predictable cost and risk is possible. Points of contact and several reports summarizing the findings of the CDEF demonstration, including links to scientific research pertaining to CDEF, are available via www.ri-water.geo.uri.edu.

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 used primarily 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 contaminant concentration to below MCL. However, CDEF technology may lower the contaminant concentration enough to permit the application of otherwise unfeasible remediation approaches, e.g., enhanced bioremediation.

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2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

Cyclodextrins are nontoxic sugars and are produced domestically in commercial quantities from corn starch. Cyclodextrins were first used for pharmaceutical purposes and in the food processing industry. The cyclodextrin molecule forms complexes with organic contaminants and, in some cases, with metals. For most nonpolar contaminants, residence in the hydrophobic interior of the cyclodextrin molecule (Figure 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.

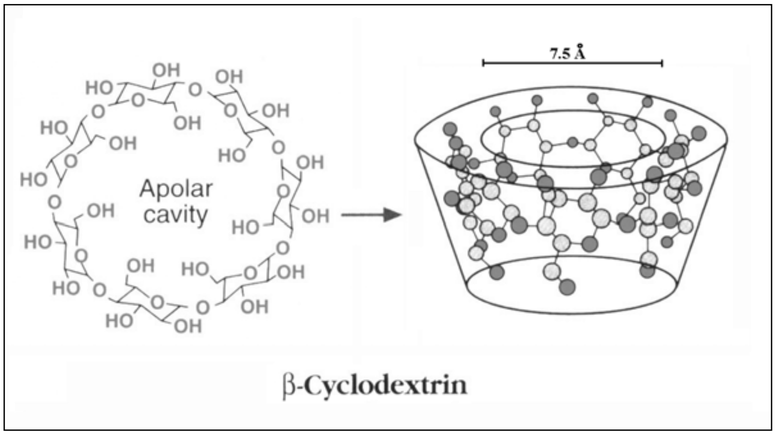

Figure 1. Two-Dimensional and Three-Dimensional Structure of the β-Cyclodextrin Molecule. (The interior of the molecule is hydrophobic and forms a complex with TCE. The exterior is hydrophilic and allows for a high water solubility of the cyclodextrin molecule [Boving and McCray, 2000]).

The particular cyclodextrin used for this demonstration is hydroxypropyl-β-cyclodextrin (HPCD). If not stated otherwise, the term "cyclodextrin" in this report refers to HPCD. 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, 1997). 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) the site is composed of localized, highly contaminated zones in heterogeneous systems; or (3) 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.

While cleaning up DNAPL contaminated sites is currently the most pressing problem, there are many other pollutants classes for which CDEF remediation technology is suitable. For example, previous field studies indicate that CD effectively removes light nonaqueous phase liquid (LNAPL) and pollutants sorbed to soil and aquifer materials (McCray et al., 2001). In addition, Wang and Brusseau (1993) showed that cyclodextrin enhances the solubility of the pesticide DDT up to 1,100 times. Similarly, CDEF significantly increased the solubility and (bio)availability of polycyclic aromatic hydrocarbons (PAH) and other petroleum hydrocarbons (Gruiz et al, 1996; Wang and Brusseau, 1998). Enhanced bioavailability, in return, may augment the bioremediation of these compounds. Cyclodextrins have been suggested for removing toxic metals, such as nickel and radiogenic isotopes from contaminated sediments (Szente et al, 1999), which could make the application of CDEF at nuclear waste sites possible. However, these applications of CDEF technology have not been field tested at this time.

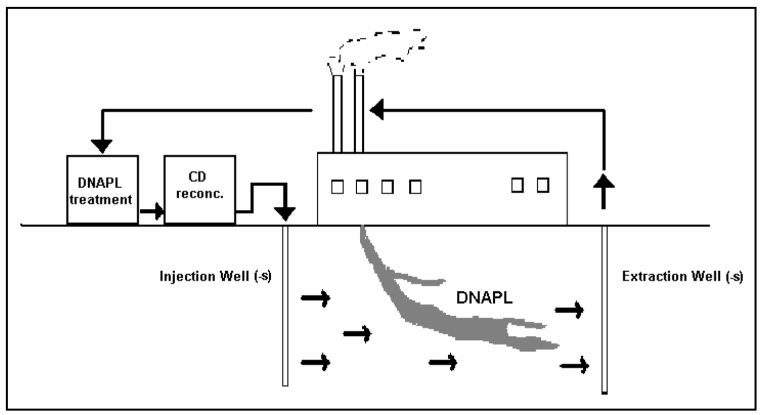

Figure 2. Conceptualized Application Scheme of the CDEF Technology.

Figure 2 shows a conceptual illustration of the CDEF. Cyclodextrin-enhanced in-situ flushing of contaminated porous media generally begins with the injection of a water-based cyclodextrin solution. There are two treatment options: using a system of designated injection and extraction wells to flush the source zone (see Figure 2) or injecting and extracting the flushing solution from one and the same wells, i.e., a push-pull operation. The first treatment option is in principle similar to conventional P&T systems. Independent of which treatment option is used, mass removal rates are faster and consequently remediation times shorter because of the advantageous solubility enhancing properties of the cyclodextrin solution. Conventional injection and extraction wells can be used to control the flowfield of the flushing solution. Because the magnitude of solubilization of organic contaminants is a linear function of the aqueous cyclodextrin concentration, the contaminant removal rate increases with the cyclodextrin concentration.

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 and stored in a 6,500 gal storage tank from which it was gravity fed into 4″ PVC injection/extraction wells. The wells were screened over the lowermost 5 ft of the Columbia aquifer. The solution containing the cyclodextrin-TCE complex was pumped to the surface and passed through a 2 μm sand filter to remove fines that may be suspended in the extract. Then the solution was passed through an air stripper. Air stripping separates the volatile contaminants from the cyclodextrin solution. TCE vapors removed from the air stream leaving the air stripper were removed by passing them through activated carbon filters. The TCE removal efficiency was largely controlled by the solution's residence time in the air stripper. To sustain the required residence times, the contaminated solution was recirculated until the desired cleanup level was reached or a lower feed rate was maintained (ranging from 1 to 5 gallons per minute [gpm]).

After passage through the air stripper, the treated CD solution was either processed in a membrane filter (UF) that enriches the cyclodextrin in the aqueous phase, or it was reinjected into the subsurface or stored in a 6,500 gal storage tank until later reinjection. This recycling of the CD limits the material needs and increases the cost-effectiveness of the technology. The permeate leaving the UF consisted of water with minimal amounts of CD and TCE levels below MCL. The permeate was discharged into a nearby storm drain. Before reinjection, the CD 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.

Prior to a CDEF application, the DNAPL treatment zone must be carefully characterized. Table 1 summarizes the minimum design parameters. The actual characterization requirements will vary from site to site. Each site requires careful evaluation of all parameters listed in Table 1. Some sites 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.

Table 1. Key Design Parameter for CDEF.

Design Parameter	Key Design Questions
Source zone characterization	• Is there evidence for NAPL? • If so, how much NAPL is present and where is it residing (i.e., what is the volume and extent of contamination)? • What is the hydraulic conductivity and thickness of the source zone and is it sufficiently large to permit CDEF? • 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	• What is the appropriate number and constellation of the well field to accomplish (1) hydraulic containment and (2) optimal capture of the CD flushing solution? • What is the (potential) influence of subsurface heterogeneities (such as hydraulic conductivity variations or stratification) on the CD delivery to the DNAPL source zone? • Into how much mass of CD must be applied to reach the cleanup target? How many sweep volumes does this amount of CD mass translate?
Treatment train	• What is the most appropriate treatment method for the contaminated groundwater? Which regulatory requirements apply? • What is the most economic pump rate relative to the cost and size of the treatment equipment? • Is recovering the CD with a UF system more economical than replacing spent CD?

During CDEF operation, aqueous samples of the extracted effluent and the injected, reconditioned flushing solution have to be collected at predetermined intervals. The principal sample parameters are the contaminant and the cyclodextrin concentration. For VOCs, standard EPA methods are appropriate for chemical analysis (e.g., purge-and-trap). Cyclodextrin concentrations can be determined with adequate accuracy using a standard total organic carbon analyzer (TOC) because, during a typical CDEF flush, the CD concentration will be orders of magnitude higher than any other compound in solution. As an added benefit, a TOC can be operated on site, which allows for real-time testing of the CD concentration. Local and state laws will dictate if and what other parameters may have to be analyzed, including the degree of treatment that has to be achieved before reinjection or discharge of effluent off site. If air stripping is used for treatment of the extracted flushing solution, periodic off-gas sampling must ensure the proper performance of the air filtration system (e.g., air-activated carbon filters). All sample locations must be properly identified and sample procedures must be specified in a work plan. In addition, Occupational Safety and Health Administration (OSHA) regulations regarding the health and safety of personnel working on a site must be followed (i.e., a health and safety plan must be prepared).

The implementation of CDEF is rather simple and requires minimal training beyond what is considered necessary for running a conventional P&T operation. The main differences are:

- Operator training for running the UF system for CD reconcentration is necessary.

- Fluctuating CD concentrations require monitoring and readjustment of the flushing solution strength. Training for performing TOC analysis of CD samples in the field and proper adjustment of CD solution is necessary.

CDEF inherits the limitations of other conventional and innovative remediation approaches that rely on the injection and extraction of liquids from the subsurface (e.g., P&T, surfactant or cosolvent flushing). The principal advantages of CDEF technology are the nontoxicity of the CD itself and its ability to quickly and effectively remove NAPL compared to conventional remediation methods such as P&T. Table 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; Boving and McCray, 2000.

CDEF is an alternative to surfactant and cosolvent flushing (Lowe et al, 1999). In principle, cosolvent-, surfactant-, and cyclodextrin-enhanced flushing are essentially a modified P&T 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).

Table 2. Characteristics of the Cyclodextrin Technology.

Property	Advantage
Nontoxic to humans and resident microbial populations	Cyclodextrins are widely used in pharmaceuticals, food processing, and cosmetics. There are minimal health-related concerns associated with the injection of cyclodextrin into the subsurface so that 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 (Brusseau et al, 1994). This is an issue of regulatory concern.
Optimal performance	Cyclodextrin's 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., a few months, which is the expected time scale of remediation), but will ultimately degrade. For comparison, surfactants often persist in the environment for long periods of time.
Highly soluble	Cyclodextrin's solubility exceeds 800 µg/L (Blanford et al, 2001). 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	Little or no 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, 1999b; Blanford et al, 2000).

As with any chemically enhanced flushing technology, losses of CD due to incomplete capture of the flushing solution are problematic, 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 of CD to maintain the desired removal efficiency of the flushing solution.

Table 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.

Table 3. Potential Risks and Limitations.

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	Bypassing of flushing solution and hampering of mass transfer results in slower remediation times.
Poor hydraulic control and incomplete capture	Losses of flushing solution and dilution of flushing solution create "dead zones."

3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

The CDEF technology demonstration was deemed successful if (1) it led to a smaller plume and shorter remediation, (2) at least 90% of the contaminant mass was removed, (3) CDEF is a reliable, versatile, easy to use method, (4) there were no undesirable side effects, such as generation of process waste or hazardous compounds, and (5) it is cost effective. The effectiveness of the demonstration was evaluated based on the performance criteria listed in Table 4 and by applying the confirmation methods summarized in Table 5 and Table 6.

Table 4. Objectives Providing the Basis for Evaluating the Performance and Cost of the CD Technology.

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance (Future)
Qualitative	Reduce contaminant source	Smaller source zone	Criterion met
	Reduce contaminant mobility	Smaller plume	Under investigation
	Faster remediation	Reach remediation goal faster	Criterion met
	Ease of use	Operator acceptance	Criterion met
Quantitative	Reduce contaminant mass	> 90%	70% to 81%
	Meet regulatory standard	< MCL $_{(TCE)}$	Criterion met for effluent
	Recycle cyclodextrin solution	> 5 flushes per molecule	Criterion not met
	Reconcentrate cyclodextrin	Recovery > 80%	Criterion met, although not in continuous UF operation mode
	Remediation time	3 months	Criterion not met
	Endpoint criteria	Effluent TCE concentration < 1% initial	Criterion not met (average TCE concentration at 22.7% of initial)
	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 gallons per day (gpd) 2) Feed rate: 5 gpm 3) CD concentration: 10% 4) Temperature: 17^0C 5) Soil type: sand (boring logs) 6) Particle size distribution: medium sand (sieve analysis) 7) Soil homogeneity: homogenous (boring logs) 8) GW pH: near pH 7 9) Dissolved oxygen (DO): 50% saturated 10) Other contaminants: no interference	7,200 gpd 1 to 5 gpm 3% to 10% 25^oC Silty sand Medium sand Heterogenous near pH 7 DO < 5% Iron precipitation

Table 5. Summary of Primary Performance Criteria Metrics and Confirmation Methods.

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		
Reduce contaminant mass	> 90% DNAPL removed	Pre- and post demonstration PTTs in combination with chemical analysis data
Hazardous materials - generated	None (except 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 5 to 10% at extraction well	TOC and TNS-complexation (fluorescence spectrophotometer)
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	Predominantly sand > 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)	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 PTT pre- and post demo test
Regulatory standard	Attain TCE MCL (5 ppb)	U of A Method (GC-FID), duplicates, spikes, trips, blanks, RPD<60%, Recovery>90%, Complete>95%

Table 6. Summary of Secondary Primary Performance Criteria Metrics and Confirmation Methods.

Performance Criteria		Expected Performance Metric (pre demo)	Performance Confirmation Method
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	Experience from demonstration operation
	Protective clothing	None	Experience from demonstration operation
Versatility			
	Continuous operation	Yes	Experience from demonstration operation
	Intermittent operation	Yes	Experience from demonstration operation
	Other application	Yes — push-pull injection	Experience from demonstration operation
Maintenance			
	Required	Activated carbon exchange Filter press clean out CD storage tank exchange	Experience from demonstration operation
Scale-up constraints			
	Engineering	Operating space	Monitoring during demonstration operation
	Flow rate	Available equipment capacity	
	Contaminant concentration	None	

3.2 SELECTION OF TEST SITE

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 bounded at the bottom by a relatively impervious layer (e.g., clay or silty-clay).
- Saturated zone not more than about 7 m (21 ft) thick.
- DNAPL mixture consisting primarily of chlorinated solvent components.
- DoD site.
- Good working relations with local stakeholders and regulators.

- Existing infrastructure (e.g. closeness to various supply stores, existing electrical and water hook-ups, shelter for analytical equipment).

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 (consisting primarily of chlorinated solvent) on other DoD sites.

3.3 TEST SITE HISTORY AND CHARACTERISTICS

Naval Amphibious Base Little Creek (NABLC), 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 borders the city of Norfolk on its western boundary. The area surrounding this 2,147-acre facility, is low lying and relatively flat with several fresh water lakes. In addition to industrial land use, NABLC is used for recreational, commercial, and residential purposes. Specifically, the southeast corner of the base was 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.

The demonstration was conducted to remove a chlorinated hydrocarbon DNAPL present in the subsurface adjacent to a former plating shop once operated by NABLC, School of Music, in Virginia Beach (Site 11). At this plating shop, chlorinated solvents and other industrial chemicals were discharged to a neutralization tank. These 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. Site 11 is located east of Building 3650, the School of Music. The Standard Industrial Classification (SIC) code for Site 11 is 3471 (electroplating, plating, polishing, anodizing, and coloring). A small building (Building 3651), the former School of Music plating shop, is directly behind the School of Music. The main groundwater contaminants identified at Site 11 are listed in Table 7.

The geologic sediments in Virginia Beach were deposited in glacial, fluvial, and marine environments during the Holocene and Pleistocene. This shallow aquifer system at Virginia Beach is composed of the Columbia aquifer, the 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. Like 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 approximately 4.6 m to 24.4 m below sea level (Smith and Harlow, 2002) (see

Table 7. Maximum VOC Concentrations in Groundwater at Site 11 Found During Hot-Spot Investigation, August 2001.

Chemical Name	Max Value (µg/L)	Max Location
Volatile Organic Compounds		
1,1,1-Trichloroethane	53,000D	LS11-GP412-11
1,1-Dichloroethane	24,000D	LS11-GP412-11
1,1-Dichloroethene	11,000D	LS11-GP412-11
Chloroform	1.000J	LS11-GP401-07
Chloromethane	2.00J	LS11-EB080401
cis-1,2-Dichloroethene	760.0J	LS11-GP410-10
Methylene chloride (Dichloromethane)	0.400J	LS11-GP401-07
Trichloroethene	390,000D	LS11-GP412-11

Figure 3 for details). Groundwater flow in the Columbia aquifer at Site 11 appears to be controlled by the overall base-wide groundwater flow direction (approximately ENE to WSW) and by seepage into a system of leaking sanitary sewer pipes that border the site on the east and south.

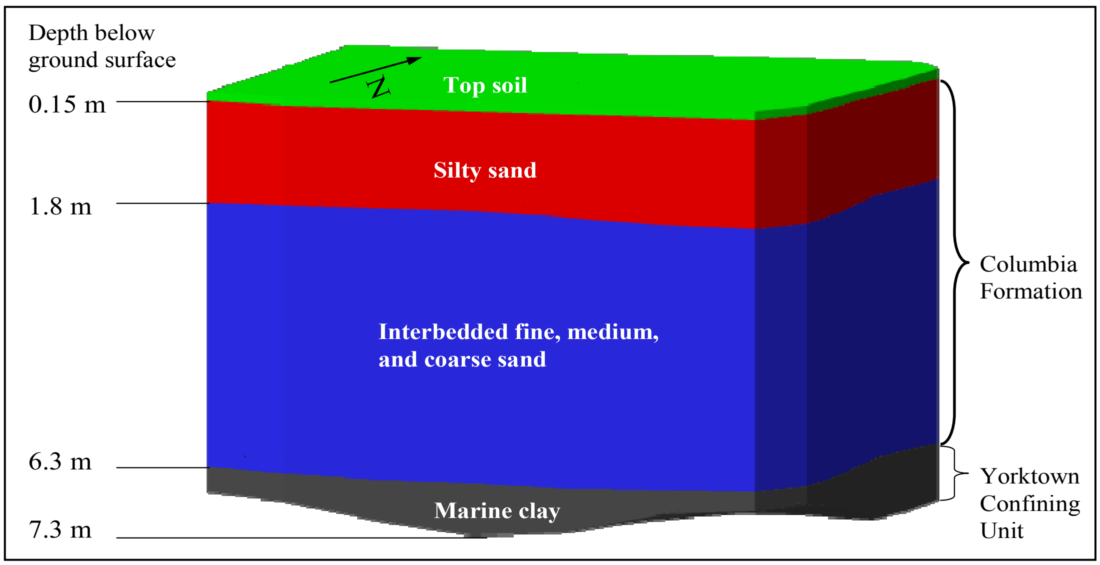

Figure 3. Simplified 3D Profile of Lithologic Formations at Site 11.
(Clay lenses encountered at some drilling locations are not shown.)

3.4 PHYSICAL SET-UP AND OPERATION

The CDEF demonstration at NABLC was carried out in several stages from June though September 2002. Site activities included well field installation, partition tracer tests before and after the technology demonstration, mobilization and demobilization of field equipment, and the actual CDEF field testing. The site layout is shown in Figure 4.

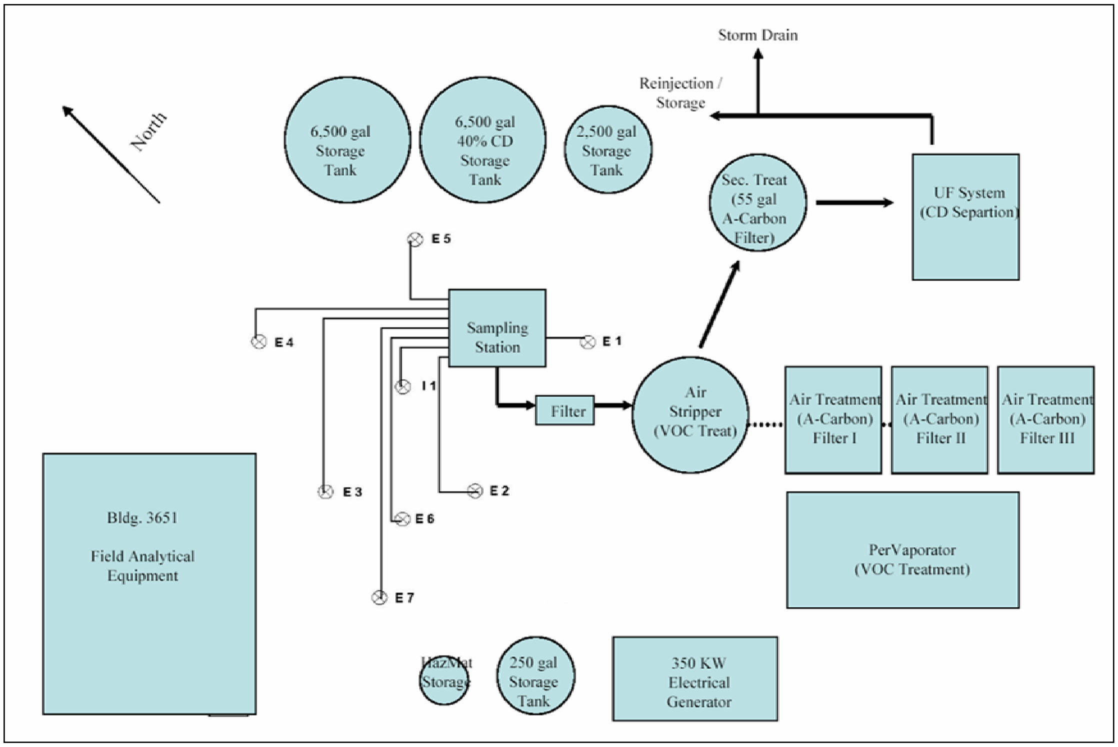

Figure 4. Site Layout During CDEF Demonstration.

The demonstration was interrupted for about 1 month (June/July) because the local publicly operated treatment works (POTW) withdrew permission to discharge treatment effluent to their system. The POTW withdrew initial consent to discharge because of a policy 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 Installation Restoration Program (IRP) at NABLC, which is 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.

No remediation operations were ongoing at Site 11 before a year after the demonstration. This demonstration was performed under the Comprehensive Environmental Response Compensation and Liability Act (CERCLA) (42 USC 9601 et seq) statutory framework. Compliance with federal, state, and local statutes was maintained as applicable or relevant and appropriate requirements (ARAR). 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 established the performance criteria listed in Table 10. Under SDWA provisions, MCLs for dissolved VOC compounds (and others) are established. A complete list of current MCLs can be obtained via http://www.epa.gov/OGWDW/mcl.html. The MCL is the remediation goal for groundwater clean up at Site 11 and needs to be reached before regulatory closeout of the site can 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.

Eight wells were drilled for the CDEF demonstration. Figure 5 shows the well locations relative to Building 3651 and the former neutralization storage tank. Also included in this figure are photoionization detector (PID) readings obtained during well drilling and the approximate extent of a trough at the base of the Columbia aquifer. This trough appears to have governed the DNAPL migration pattern at the site, i.e., it directed DNAPL transport towards (and under) the building. The existence of the trough was unknown prior to drilling and necessitated modifications of the planned well field design and flushing scheme. The most important deviation from the demonstration plan was a shift of the treatment zone away from the five-star pattern described by wells E1 through E5 (where "E" designated extraction wells) and a central injection well (I1). The revised treatment zone was centered around well E6 and included wells I1, E2, E3, and E7 all of which were used as extraction or injection wells. A line-drive and a push-pull treatment scheme were tested. During the line-drive tests, 20% cyclodextrin solution was injected into wells E2, E6, and E7 and extracted from wells E3 and I1. Well E6 was converted to an extraction well about half-way into the line-drive test to achieve better control of the flow field.

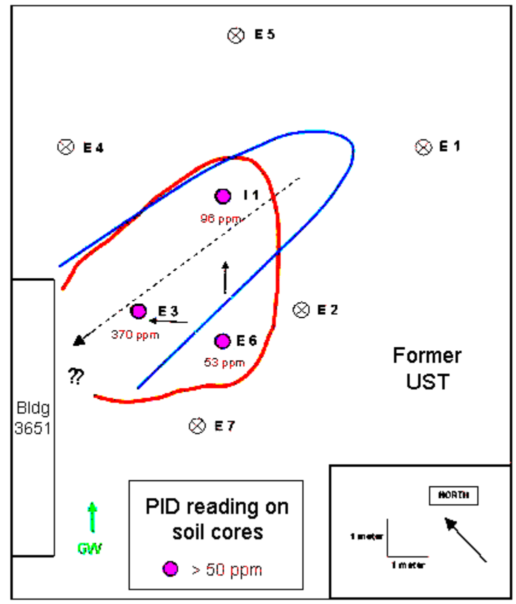

Figure 5. Location of Wells Drilled for the CDEF Demonstration in Relation to Building 3651. (Well E 6 marks the approximate location of a former underground neutralization tank. PID readings were taken on soil cores during well installation. Also shown (by the blue line) is the approximate extent of trough discovered during drilling. The trough axis (dashed line) slopes towards building 3651. The red line marks the approximate extent of the source zone. Note that groundwater (GW) flow at time of drilling was as indicated. However, GW flow direction changed by 180^O during the course of the demonstration.)

During the push-pull tests, cyclodextrin solution was injected and then extracted from wells I1, E3 and E6. Push-pull tests were either conducted on one well at a time or on all wells simultaneously.

3.5 SAMPLING/MONITORING

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, DO, 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.

Table 8 summarizes the sampling frequency and other sampling details. The principal sampling locations included injection and extraction wells, effluent discharge point, monitoring wells located in the vicinity of the demonstration site, and influent and effluent of the above ground treatment system (air stripper, UF system). Additional samples were collected from 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 and as the activated carbon filters for monitoring the ambient air quality. These air samples were not used for mass balancing. Cyclodextrin and bromide concentrations were determined on site. Confirmatory samples were sent to Reed & Associates in Newport News, Virginia). All other aqueous samples were stored in an on-site refrigerator until express-shipped in coolers to the University of Arizona laboratory.

Table 8. Daily Sample Summary as Provided in Demonstration Plan.

			Field Samples			Quality Assurance Samples		
Sample Matrix	**Analysis**	**Method**	**Number of Locations**	**Samples Per Location**	**Total Per Day**	**Duplicates**	**Trip Blanks**	**Total Groundwater**
GW	Target VOCs	GC	8	1 / 6hr	24	10% of total field number	1 per cooler	2 to 4
GW	CD	TOC & RF	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

Actual sampling frequency was generally higher, i.e., more samples were collected for technology assessment purposes than necessary during a typical CDEF remediation. TOC: total organic carbon analyzer. RF: fluorescence spectrometry. GC: gas chromatography.

3.6 ANALYTICAL PROCEDURES

The analytical procedures, including quality assurance/quality control (QA/QC) requirements, were followed as outlined in the demonstration plan with the exception of two non-toxic conservative tracers that were added for the post-demonstration partition tracer test (fluorescein and deuterium). These tracers were added to prevent possible interference with bromide tracer remnants from the predemonstration partition tracer test. Table 9 summarizes the analytical methods used for this demonstration.

Table 9. Analytical Methodology Summary.

Analyte Type	Matrix	Method Name	Container Type	Container Size	Preservative	Analysis Location
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 Alc/F/D: UA
Confirmatory Samples	GW	GC-MS	glass	40 ml	Yes	Reed & Associates

UA: University of Arizona, Allc: alcohol tracer (PTT), F: fluorescein, D: deuterium, Br^-: bromide. TOC: total organic carbon analyzer.
RF: fluorescence spectrometry. GC: gas chromatography.

The VOC analytical methods used in the University of Arizona (UA) laboratory were similar to standard EPA methods, but were adapted for the presence of CD in the aqueous phase. Selected samples (confirmatory samples for effluent) were sent to a local laboratory, Reed & Associates in Newport News, because of shorter turnaround times.

During the predemonstration PTT, TCE concentration was also measured in the field using a portable GC. However, once cyclodextrin was present in the groundwater, i.e., after the first CD injection/extraction tests, the field GC regularly produced lower TCE concentrations compared to those determined in the UA and Reed & Associates laboratories. The discrepancy between the field GC results and laboratory results were caused by the complexation of TCE by the CD. Because the field GC method could not be adjusted to account for this discrepancy (e.g., by adding a purge-and-trap system), all samples collected during subsequent tests were sent to the laboratory at UA. The CD concentration was analyzed on site using a TOC and was later verified in the URI lab against a control method based on fluorescence spectrometry (RF). For further details regarding the analytical procedures, refer to the demonstration plan.

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4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE DATA

The format of the performance data summarized in Table 10 follows the recommendation of the Federal Remediation Technologies Roundtable (FRTR, 1998).

Table 10. Performance Data for CDEF Demonstration at NABLC.

Types of samples collected	Aqueous samples (flushing solution, waste water) analyzed for TCE, 1,1,1-TCA, 1,1-DCE, chloroform, and cyclodextrin
Sample frequency	Several times daily
Quantity of material treated	About 50 tons of DNAPL source zone material (in situ)
Untreated and treated contaminant concentrations	Substantial changes in groundwater TCE concentrations measured after end of demonstration (average TCE concentrations decreased 77.3%)
Cleanup objectives	TCE mass removal > 90%
Comparison with cleanup objectives	70%-81% of mass was removed based on partition tracer tests and mass balance calculations (approximately 30 liters TCE, 1,1,1-TCA, 1,1-DCE)
Method of analyses	VOC: GC-FID CD: TOC and RF
QA/QC	Detailed QA/QC protocols in demonstration plan
Residues	VOC off-gas, decontamination fluids, fluids leftover from on-site chemical analysis

4.2 PERFORMANCE CRITERIA

The primary and secondary performance criteria used for the evaluation of CDEF were established in the demonstration plan. Table 11 and Table 12 summarize these criteria.

Well clogging due to iron precipitation in the injection wells made continuous injection and extraction of the cyclodextrin solution in closed-loop mode impossible. The iron precipitation may have been prevented by installing an anaerobic air stripper system. Time and budget constraints, however, prohibited the installation. In response to this unanticipated problem and in deviation from the demonstration plan, the CDEF application scheme was modified in favor of the (discontinuous) push-pull approach.

Table 11. Expected and Actual Primary Performance and Performance Confirmation Methods. (Refer to demonstration plan for details.)

Performance Criteria	Expected Performance Metric (Pre Demo)	Performance Confirmation Method	Actual (Post Demo)
PRIMARY CRITERIA (Qualitative)			
Contaminant mobility	Reduced smaller plume	Monitoring wells LS11 -MW02, -MW01T, -MW04D, -MW05D	Under investigation[a]
Faster remediation	Endpoint attained faster	Monitoring wells LS11 -MW02, -MW01T, -MW04D, -MW05D	TCE concentration declined by 77.3% on average
Ease of use	Minimal operator training required	Demo experience	Except for UF system, minimal training required
PRIMARY PERFORMANCE CRITERIA (Quantitative)			
Hazardous materials - generated	None	Analysis for possible toxic degradation products	None directly related to CDEF
Factors Affecting Technology Performance			
Flow rate	64 m^3/d (18,000 gpd)	Certified ABB flow meter (Accuracy ±3%)	27.2 m^3/d (7,200 gpd)
Feed rate	0.5 m^3 / hr	Certified ABB flow meter (Accuracy ±3%)	0.25 to 1 m^3/hr (1 to 5 gpm)
CD concentration	20 to 40% at injection well 5 to 10% at extraction well	TNS-complexation (RF) and TOC analysis	20 to 35% at injection well 2.7 to 6% at extraction well during line-drive, 5% to 33% during push-pull
Soil type	> 100 ft/d hydraulic conductivity (medium sand with some silty clayey strata)	Pre demo slug test	2.4 to 25 ft/d hydraulic conductivity (medium sand, some silty-clayey layers)
Particle size distribution	Fraction < 0.063 mm (very fine sand) is less than 10%	Sieve analysis of cores (ASTM D422-63 method)	Locally, high silt and clay fraction
Soil homogeneity	Predominantly sandy material > 90% of screened interval	Thickness of strata in soil boring profile	Predominantly sandy material > 90% of screened interval
GW pH	pH varies between 6 and 8	Orion pH meter (Accuracy ±5%)	pH between 6 and 7
DO	DO varies between 50 to 90% saturation	YSI 55 DO meter (Accuracy +/- 5%)	DO < 5%
Target contaminant			
% reduction	Reduce TCE by 90%	Mass balance in combination with PTT pre- and post demo test	70% - 81% reduction
Regulatory standard	Attain TCE MCL (5 ppb)	UA Method (GC-FID), duplicates, spikes, trip, blanks, RPD<60%, Recovery>90%, Complete>95%	MCL attained in air stripper effluent. GW concentration still exceeds MCL in most wells.

[a] The effect of the CDEF demonstration on the TCE plume size is currently not known. NABLC is planning an extensive sampling campaign (including MIP and Geoprobe measurements) in September 2003. This field campaign will follow-up on the predemonstration hot-spot investigation conducted in August 2001 and should give conclusive information about how the demonstration affected the TCE plume at Site 11.

Table 12. Expected and Actual Secondary Performance and Performance Confirmation Methods. (Refer to demonstration plan for details.)

Performance Criteria	Expected Performance Metric (Pre Demo)	Performance Confirmation Method	Actual (Post Demo)
SECONDARY PERFORMANCE CRITERIA (Quantitative)			
Process Waste			
Generated	None	Observation	On-site chemical analysis fluids
Plume Size	Smaller	Monitoring wells LS11 -MW02, -MW01T, -MW04D, -MW05D	Under investigation
Reliability			
Downtime due to equipment failure	< 5% of demonstration time	Record keeping	ca. 25% of demonstration time
Safety			
Hazards	None	Demo experience	None
Protective clothing	None	Demo experience	None
Versatility			
Continues operation	Yes	Demo experience	Yes (line-drive) No (push-pull)
Other application	Yes	Demo experience	Low DO indicates degradation of CD — enhanced biodegradation ?
Maintenance			
Required	Activated carbon exchange Filter press clean out CD storage tank exchange	Demo experience	A-carbon exchange, sand filter cleaning, well rehabilitation, UF back-flushing
Scale-up constraints			
Engineering	Operating space	Monitoring during demonstration operation	Site-specific
Flow rate	Available equipment capacity		Budget constrains
Contaminant concentration	None		Presence of NAPL — not for plume treatment

4.3 PERFORMANCE ASSESSMENT

The data gathered during the CDEF demonstration illustrate that most, but not all, of the performance objectives have been met (see demonstration plan). First, CDEF technology proved to enhance the removal of TCE and other VOCs under full-scale operating conditions. The amount of DNAPL was reduced by 70% to 81% (based on pre- and post-PTTs and mass balance calculations), which is 9% to 20% short of the performance objective >90% DNAPL removal. The TCE concentrations in the reference wells declined by 78% on average. The original performance objectives for this demonstration were to remove >90% of the DNAPL mass and reduce the aqueous TCE concentration to <1% of the initial TCE concentration. Neither criterion was met during the comparably short duration of this demonstration. The less than expected performance in terms of decreasing the aqueous TCE concentration underlines the fact that CDEF is primarily a source zone treatment technology that, like most other chemical enhanced treatment approaches, must be assisted by other (subsequent) remediation approaches. The MCL, however, was reached for effluent treated by air stripping. These results were achieved within 2 months of active remediation (not counting time spent on site mobilization/ demobilization and tracer tests). Thus, during the relatively short period of this demonstration, a significant amount of contaminant mass was removed, which will eventually translate in shorter remediation duration once a decision is made how to cleanup Site 11.

Table 13 shows that during all CDEF tests (line-drive and push-pull) about 29% of the total 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 relative to the other tests.

Table 13. Overall Mass Balance Yielding the Approximate 30 L Removal Estimate Cited in the Report, As Well As the Estimated Mass Remaining After All Testing.

Test or Activity	Voc Mass Removed (g)	DNAPL Volume Removed[1] (liters)	Percentage of DNAPL Mass Removed During Demonstration [2] (%)	Percentage of DNAPL Remaining In Subsurface [3] (%)
Pretest 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 multiwell 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 beginning 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.

The demonstration of CDEF in push-pull operation was not anticipated in the demonstration plan. However, the same performance objectives and assessment strategies for the evaluation of the CDEF line-drive demonstration were applied. Of the two treatment schemes, push-pull evidently outperformed the line-drive demonstration. For example, during push-pull the average solubility of TCE increased up to 6.5 times over conventional P&T, whereas it increased only up to 3.2 times during line-drive. Also, the highest aqueous TCE concentrations measured during the CDEF demonstration were >200 mg/L or up to 9 times higher than the average pretreatment TCE concentrations. Even higher solubility enhancements (up to 19 times) were observed for 1,1,1-TCA. These values demonstrate clearly that CDEF significantly enhanced the contaminant removal rates. (see Figure 6). Cyclodextrin concentrations were easily monitored in real time by using an

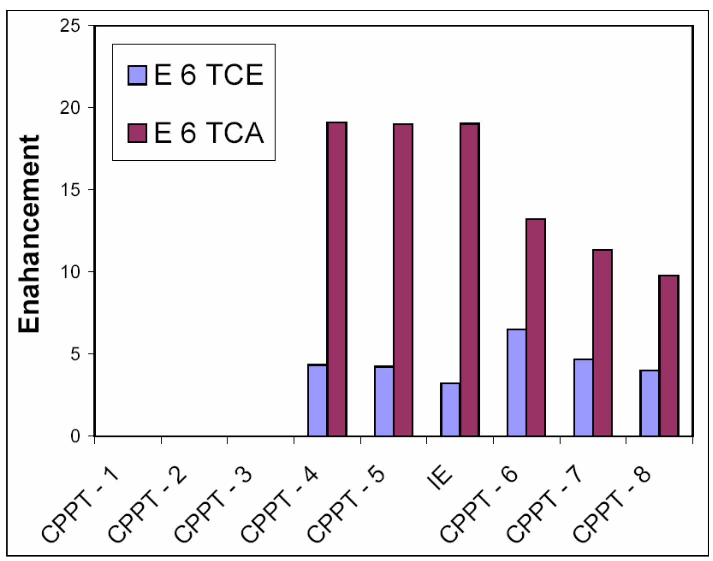

Figure 6. Average Solubilization Enhancements During Line-Drive (IE) and Push-Pull Tests. (Note that the solubilization of 1,1,1-TCA is enhanced much more compared to TCE.)

on-site TOC analyzer. On-site measurements of aqueous TCE concentration using a gas chromatograph without purge-and-trap capabilities proved unreliable.

Compared to similar treatment approaches (e.g., P&T, in-situ oxidation), our experience with CDEF demonstrates that this technology is easy to use. The only pieces of equipment that required special training[1] were the UF system used for CD reconcentration and on-site analytical equipment (i.e., GC and TOC). During operation (either in line-drive or push-pull mode), the CD concentration of the flushing solution has to be monitored and, if necessary, adjusted. The use of in-line analytical equipment and remote control of the CDEF operation (including installation of automatic mixing valves) can significantly decrease the number of onsite operating hours. Regular maintenance of the UF system was required (e.g., back-flushing membrane filters). The air stripper required infrequent decontamination to remove iron precipitates (a site specific problem). With regard to health and safety requirements, none of the processes and technologies involved in CDEF remediation poses risks that exceed those of comparable remediation approaches. In fact, CD is preferable over many other remediation agents (such as permanganate or many cosolvent/surfactant formulations) because it is nontoxic and appears to readily (bio)degrade.

However, there were some unanticipated technical problems that affected the overall performance of this remediation technology. For example, the aeration of the flushing solution during air stripping resulted in the precipitation of iron inside the air stripper, and more important, clogging of the injection wells. Besides increased air stripper maintenance time, the clogged injection wells did not permit continuous operation of CDEF in line-drive mode at this demonstration site. Although time and budget constraints during this demonstration prevented us from taking appropriate countermeasures, there are commercial solutions available to run an air stripper under anaerobic conditions (e.g., under a nitrogen atmosphere). Conversely, well clogging was avoided by using the push-pull approach. This was because the recycled CD flushing solution — after passing through the air stripper — quickly became anaerobic again when kept in on-site storage tanks for 12 to 24 hours (depending on outside temperature). It appears that the naturally occurring degradation of the CD consumed the DO present in the flushing solution. The rate at which the CD was degraded, however, was slow and did not cause any noticeable CD mass losses or changes in the effectiveness of the flushing solution. The additional holding time did not delay the remediation because sufficient storage capacity existed at the site (two 6,500 gal commercial storage tanks) and at least 12 hours passed between extraction and reinjection of the flushing solution.

Another issue was the lower than expected treatment capacity of the UF system. The UF was designed to treat 5 gpm on a continuous basis and increase the CD concentration to 20% in the process. The actual flow rates achieved ranged between 0.5 and 2 gpm. A scale-up (i.e., using a larger membrane area) would have been required to permit in-line, continuous operation.

[1] The use of a pervaporation system for VOC removal from the flushing solution was also field tested. However, the cost and performance assessment of the pervaporation system was inconclusive because the equipment was damaged during site mobilization. When operational, the pervaporation system removed up to 99% of VOC, but it required a significant amount of electrical energy and constant supervision by a field engineer. It also generated a stream of highly VOC-enriched waste water. Based on our field experience with this treatment approach (and compared to the air stripper system we used), we cannot recommend pervaporation technology.

Although the flow rates did not permit continuous operation of the UF in-line, the desired concentration enhancement to 20% was achieved. Thus, the usefulness of the UF system for CD reconcentration was demonstrated.

4.4 TECHNOLOGY COMPARISON

Table 14 provides a technology comparison of CDEF to selected alternative DNAPL removal technologies and conventional P&T technology. 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. The need for site characterization and the difficulty in adequately describing all its aspects have direct impact on the design, cost, and performance of all technologies.

Table 14. Technology Comparison: Advantages and Disadvantages of Selected DNAPL Removal Technologies
(Modified from NFESC 2001.)

	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 • Locate source zone and delineate its extent • Map hydrostratigraphy • Measure basic aquifer and soil parameters • Characterize the capillary barrier (aquitard) relative to NAPL mobilization design Simulation of well field design and injection/extraction scheme	Detailed site characterization required • Locate source zone and delineate its extent • Map hydrostratigraphy • Measure basic aquifer and soil parameters • Characterize the capillary barrier (aquitard) relative to NAPL mobilization design Simulation of well field design and injection/extraction scheme	Detailed site characterization required • Locate source zone and delineate its extent • Map hydrostratigraphy • Measure basic aquifer and soil parameters Simulation of well field design and injection/extraction scheme	Detailed site characterization required • Locate source zone and delineate its extent • Map hydrostratigraphy • Measure basic aquifer and soil parameters 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
Effect on subsurface	Demonstrated reduction in NAPL saturation to less than 0.05%	Demonstrated reduction of DNAPL saturation by 20% at site with low initial DNAPL saturation (Sn=0.7%). Long-term effects may include enhanced biodegradation facilitate by cometabolism 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 to 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 for concern.	NAPL mobilization is generally not a cause for concern.	NAPL mobilization is generally not a cause for concern.
Performance assessment	Surfactant residuals in the subsurface may affect performance assessment by PTT.	PTT can be used for performance assessment.	Limited by dissolution rate of NAPL. Change in NAPL composition can affect performance assessment.	PTT can be used for performance assessment.

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5.0 COST ASSESSMENT

5.1 COST REPORTING

The cost report for the CDEF technology was prepared based on guidelines provided by the Federal Remediation Technologies Roundtables (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 those employed at NABLC. However, a few modifications have been made based on lessons learned during the CDEF demonstration. These modifications, where applicable, are outlined in the following paragraphs.

Table 15 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 15. Summary of the Actual Demonstration Site Conditions at Site 11, NABLC.

Parameter	Value
Depth to water table	2.1-2.4 m below ground surface (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 concentration [(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)] Total DNAPL volume recovered during entire demonstration was approximately 30 liters (based on TCE, 1,1,1-TCA, and 1,1-DCE concentrations in extracted solutions). Difference in DNAPL saturation between pre-PTT and post-PTT indicated that this volume equals 70% to 81% DNAPL mass removal. Thus, about 38 liter DNAPL was initially present at demonstration site, 90% of which are 34.2 liter.

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 an 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 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 (including PTTs). A detailed cost report is provided in Appendix B. Based on the mass of VOC contaminants removed and treated during the flushing with CD (25.8 lbs[2]), 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 tests 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 (I/E and CPPT) were tested, 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. 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.

For this real-world cost assessment, all one-time, demonstration-related costs were removed (such as experimentation, process optimization, nonrouting analysis and testing, and excessive sampling and analysis used to evaluate and refine the demonstration). It was assumed that one VOC and two CD analyses were carried out on a daily basis (see Table 16) over a period of 2 months. It was further assumed that no pervaporation equipment was used and that no partition

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

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 C. 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.

Table 16. Criteria Used to Develop Remediation Cost, CD Recovery Cost, and Full-Scale Remediation Time Estimates.

Criterion	Value
Type of CD	Hydroxyl-β-cyclodextrin; technical grade; unstabilized 40% aqueous solution with pH near neutral
Treatment area	30 m^2 (300 ft^2) small site 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% 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% Continuous operation: 79%
Efficiency of CD recovery by UF (batch mode)	Batch operation: 90% Continuous operation: 68%
CDEF operation time	I/E: Continuous 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) 2 x 21,000 gal tank (full-scale)
Analytical requirements [(d)]	Continuous operation: 1 VOC and 2 CD analyses per day Batch operation: 1 VOC and 2 CD analyses per flush
Labor requirements [(e)]	Continuous operation: 6 man hrs per day 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 multiwell 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 was required for 40% CD stock solution storage; second tank was required for storage of recovered CD flushing solution.
[(d)] One VOC analysis of the extracted and injected solution per day was performed to monitor remediation progress and efficiency, one CD analysis of the extract to confirm effectiveness of the flushing solution, and a second CD analysis after UF system to confirm flushing solution target concentration of 20% before reinjection. 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, assuming that the 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).

Hypothetical Full-Scale System. Another significant difference between this ESTCP technology demonstration and a real-world implementation of CDEF technology was the comparably small size of the treatment zone and the scale at which the demonstration was performed (see Table 15). 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 15) 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 16 summarizes the remediation system performance parameters used to calculate remediation cost and duration.

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

The full-scale cost report was based on 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[3].

Two different treatment approaches were evaluated: line-drive (I/E) and multiwell 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 (Table 16). This conservative estimate leaves ample room for cost improvements because the UF used in the demonstration was a comparably low-efficient proto-type. Finally, a cost assessment was provided in case no UF system is used. Table 17 summarizes the various scenarios assessed and provides a comparison of the number of wells needed for treating at full scale.

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

Table 17. Comparison of Well Requirements for Full-Scale CDEF Application (2,500 ft^2) at a Hypothetical Site Similar to NABLC.

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 to injection, extraction, or hydraulic control wells used during I/E.
[2] No hydraulic control wells are necessary if groundwater flow velocities are 0.5 cm or less.

An EXCEL model was developed to estimate remediation duration and amount of CD mass needed for achieving the 90% DNAPL mass removal criterion. The model requires as input most of the data summarized in Table 15, Table 16, and Table 17. 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 IV.

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 D). The full-scale CDEF flushing durations for each treatment scenario are summarized in Table 18.

Table 18. Comparison of Full-Scale CDEF Flushing Durations at a Hypothetical Site Under Conditions Similar to Those at NABLC.

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 total life-cycle costs for the three full-scale CDEF treatment scenarios with a UF in operation are summarized in Table 19. 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 E. A second full-scale cost assessment was developed for a smaller site (see Table 16). Refer to Appendix F for details. Table 20 shows the implementation cost at the smaller site.

Table 19. Cost of Full-Scale CDEF Implementation (Treatment Area: 234 m^2 or 2,500 ft^2).

Cost Category	Subcategory	Cost Scenario: I/E Approach With UF (Continuous Mode)	Cost Scenario: CPPT Approach With UF (Continuous Mode)	Cost Scenario: 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–nonprocess equipment	$11,300	$8,050	$11,300
	Other — installation	$119,303	$117,854	$117,854
	Subtotal:	**$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
	Subtotal:	**$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
	Subtotal:	**$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 20. Cost of Full-Scale CDEF Implementation (Treatment Area: 30 m^2 or 300 ft^2).

Cost Category	Sub Category	Cost Scenario: I/E Approach With UF (Continuous Mode)	Cost Scenario: CPPT Approach With UF (Continuous Mode)	Cost Scenario: 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 investigation	$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–nonprocess equipment	$8,050	$8,050	$8,050
	Other — installation	$36,784	$32,229	$32,229
	Subtotal:	**$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
	Subtotal:	**$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
	Subtotal:	**$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**	**$8,231**
	Quantity treated – VOC mass (lbs)	**105**	**105**	**105**
	Unit cost (per lbs VOC removed and treated)	**$6,871**	**$3,789**	**$3,883**

5.2 COST ANALYSIS

Compared to the actual demonstration cost, the real-world CDEF implementation cost is approximately 55% less. The difference is attributed to one-time, demonstration-related costs, such as experimentation, process optimization, nonrouting 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 multiwell 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., the 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 to the push-pull approach, significantly more CD was needed because of the comparably low CD recovery efficiencies during line-drive flushing. Another cost driver was the comparably long remediation time necessary (19 months) when implementing the line-drive approach at large scale sites (see Table 18). Longer remediation times resulted in much higher labor and equipment rental and purchase cost compared to the shorter multiwell push-pull treatment scenarios.

The lowest costs overall were realized by implementing multiwell 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 to run in continuous mode, the amount of CD needed would increase 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 20). 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 18). 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 that 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.

5.3 COST COMPARISON

In this section, the cost of CDEF treatment for DNAPL removal is compared to the cost of a conventional remediation technology (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 NABLC (Section 5.1 and 5.2). As Table 21 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 (MCB) Camp Lejeune, North Carolina (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 NABLC (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 (including 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 21. Comparison of Site Conditions at NABLC, and MCB Camp Lejeune, North Carolina. (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) 40 push-pull	46 line-drive (1)
Type of treatment	Enhanced flushing	Enhanced flushing
Flushing agent	Cyclodextrin (20 wt%)	Surfactant (4 wt%) Cosolvent (8 wt%)
Treatment flow rate	6 gpm	6 gpm
Duration of operation	19 months (I/E) 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 (SN) is PTT-based
(3) See NFESC, 2001, p. 72.

Table 22 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 costs were incurred over a 30-year period. All costs were based on present value (NFESC, 2001). The treatment alternative, "multiwell push-pull with UF operating in continuous mode," was not included in Table 22 because, unless a more effective UF system becomes available, this approach cannot compete with the multiwell push-pull approach and with the UF running in batch mode.

Based on the cost comparison provided in Table 22, CDEF in push-pull mode can compete with SEAR. Both innovative remediation technologies are only a 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 reduces the hazardous waste exposure time and results in returning a site to the real estate market much earlier (or permits earlier re-use). CDEF in line-drive operation was the most expensive innovative remediation technology, and resistive heating was the least expensive.

Table 22. Summary of CDEF and Alternative Technology Cost for Full-Scale Application for Remediation of a DNAPL Source Zone Similar to NABLC. (All costs are 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	$498,000	$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 CL (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 NABLC.
[2] The cost of characterizing DNAPL source zone before and after treatment is not included. 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 (NFESC, 2001).

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 nontoxic 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. Future advances in treatment technology, such as the availability of a more effective UF filter material, may decrease the implementation cost.

6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

Much effort went into preparation of the CDEF demonstration, including extensive site investigations and negotiations with regulators and suppliers of specialized equipment and services. In several instances, these efforts were wasted. A few of the unexpected obstacles encountered include:

- Withdraw of consent to discharge to POTW
- Damaged equipment
- Treatment zone heterogeneities
- 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 ease of adapting the CDEF system to changing boundary conditions. Problems that could not be solved in the field, e.g., repair of damaged equipment, required in a few instances modification or scaling back of the demonstration objectives.

Procurement issues: Although this was the first time a membrane filter was used for cyclodextrin recovery, the underlying technology is commercial off-the-shelf (COTS). All other major pieces of equipment (e.g., air stripper, UF, sand filters, and pumps) 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 more than 6 to 8 months of remediation time.

6.2 PERFORMANCE OBSERVATIONS

In deviation from the demonstration plan (see Appendix I), CDEF was implemented in continuous line-drive fashion as well as push-pull mode. The reasons that led to the change of the implementation approach have been outlined in Section 4 and in the CDEF Final Report (Boving et al, 2003). Also, delays imposed from the outside (e.g., base security and withdrawal of consent to discharge to POTW) affected the progress and performance of the demonstration. Consequently, not all performance criteria were met. Most notably, the DNAPL saturation after the end of the demonstration was not reduced by 90% (actual reduction was approximately 81%) and the end-point criteria of attaining the MCL for TCE was not reached. While the first criterion most likely would have been reached if the demonstration had continued for a few more weeks, the second criterion would not have been reached even if the treatment had continued. In retrospect, setting the remediation end point at MCL level was never realistic because, at most sites, enhanced flushing technology is implemented to remove the bulk DNAPL mass. Once removed, other remedial approaches, such as natural attenuation, take over and target the remaining contaminants more effectively. A more realistic end-point criterion would be the threshold concentration below which natural attenuation becomes effective. This concentration, however, is strongly site-specific and this criterion may not be applicable to every site.

6.3 SCALE-UP

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. Because the major pieces of equipment are COTS, up-scaling CDEF should not be problematic. Of all pieces of equipment, the UF requires the largest investments (either rental or purchase) and may be custom ordered to suite the scale of a remedial operation. Because of the limited number of vendors, UF rental or purchase costs are comparably high and depend in part on availability of adequately sized filtration systems.

The cost of cyclodextrin appears to be linked to the price of corn (CD is manufactured from corn starch). Thus, CD cost may fluctuate and may vary significantly on the international market.

To the best of our knowledge, no patents or other proprietary claims complicate the adaptation of CDEF technology.

6.4 OTHER SIGNIFICANT OBSERVATIONS

The injection of any kind of flushing solution, including cyclodextrin, into the subsurface requires sufficiently high permeability ($>> 1x10^{-5}$ cm sec^{-1}) of the DNAPL source zone. If lower permeability strata are treated or if the treatment zone is very heterogeneous, the overall treatment duration (and success) will be determined by these low permeability zones. Thus, there are certain sites at which CDEF technology should not be considered.

The implementation of remediation technologies requires frequent and unhindered access to the field site. Unless a significant amount of money is spent on remote site surveillance and fully automated sample collection/analysis, access to military sites likely becomes restricted during times of national crisis (as was the case during this demonstration). Under these circumstances, system shut-downs may become necessary and can lead to the loss of hydraulic control of the flushing solution. Preventive hydraulic control measures need to be considered to prevent this loss from happening.

6.5 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 from this demonstration.

CDEF outperformed conventional P&T. 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) as conventional P&T.

CPPT approach outperformed I/E approach. The assessment of line-drive and push-pull treatment approaches showed that CPPT outperformed the I/E in several ways. For example, CPPT is significantly cheaper than I/E and most likely achieves the remediation goals 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.

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 VOC-enriched effluent that had to be disposed of off site or, if available, in an adequate on-site treatment facility. The air stripper, on the other hand, did not produce any hazardous waste. 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 reliable cost assessment of the PVP system, the overall cost of operating a PVP was significantly higher when compared to air stripping technology.

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 that the PTT results be supported by other mass balancing means, for example by membrane interface probe (MIP) or Geoprobe measurements. 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, possibly resulting in a miss of the tracer breakthrough.

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 NABLC base was very strict. Personnel working on base were subjected to extensive background checks lasting from a few days to 2 weeks. These security requirements caused significant delays bringing in personnel (e.g., truck drivers or service technicians) without prior security clearance. This had direct consequences for the demonstration because fast response 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. A local consultant could have assisted in obtaining unforeseen services and in negotiating with suppliers, giving the Principal Investigator (PI) more time to spend on advancing the demonstration.

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

6.6 END-USER ISSUES

This demonstration has received national and international attention. For example, the cyclodextrin technology was featured in *Business Week*, the *Civil Engineering Magazine*, and in radio interviews. Presentations of the CDEF technology have been given for interested parties in the environmental remediation industry and to the scientific community. CDEF technology has been presented on more than 20 occasions, including papers that have appeared in scientific journals. A Website (www.cyclodextrin.geo.uri.edu) under construction to promote CDEF technology will provide links to this report and other technical and scientific information pertaining to CDEF.

As a direct result of this CDEF demonstration and the information dissemination efforts, several applications of modified cyclodextrin technology are already under way or planned for the immediate future (e.g., Patrick Air Force Base, Florida). National and international consulting companies are making many inquiries about this CDEF demonstration. Those directed to NABLC are forwarded to the PIs of this report. Finally, NABLC is considering CDEF as one of several remediation approaches that may be implemented at Site 11.

6.7 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. About a year before the ESTCP demonstration, a Partnering Meeting was held to present the concept of the study. At this meeting, which was attended by VADEQ, Navy, EPA, CH2MHill, and all PIs of this project, the technology was presented, and a discussion followed on 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.

A kickoff meeting was held at NABLC. This meeting established the rules for 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 or agencies. The community was informed of the CDEF activities at Site 11 via the NABLC Restoration Advisory Board (RAB), which consisted of members from the public, regulators, and members of the military environmental restoration community. The exchange of information and results with NABLC are still taking place.

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APPENDIX A

POINTS OF CONTACT

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Stephanie McManus	Commanding Officer Naval Amphibious Base Little Creek Base Civil Engineering, Environmental 1450 Gator Boulevard Norfolk, VA 23521-2616	(757) 462-2517 (757) 462-7060	NAB Little Creek Environmental Supervisor
John Ballinger			Community Outreach Coordinator
NAB Little Creek and other contacts			
Glenn Roundtree	Commanding Officer NAB Little Creek Base Civil Engineering, Environmental 1450 Gator Boulevard Virginia Beach, VA 23521-2616	(757) 462-2517	NAB Little Creek contact
NAB Little Creek Response Operator	NAB Little Creek Virginia Beach, VA 23455	x4444 (on base) (757) 363-4444 (off base)	Security/Fire/ Ambulance

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APPENDIX B

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	Power Consumption in: KW	Number of wells, type and depth needed for remediation
Soil mass: 49.3 tons	Cost / KWH $ 0.05725	3 injection wells (22.5 ft)
	Note: Most electrical power was provided by generators.	3 extraction wells (22.5 ft)
PI : Principal Investigator		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 C

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	Power Consumption in: KW	Number of wells, type and depth needed for remediation
Soil mass:	49.3 tons	Cost / KWH $ 0.05725	3 injection wells (22.5 ft)
		Note: Most electrical power was provided by generators.	3 extraction wells (22.5 ft)
Treatment duration:	2 months		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)

Units	No of units	Unit labor cost	Unit mat cost	Labor cost	Mat cost	Item cost	Total cost	Item description
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**

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APPENDIX D

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**

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 E

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 Cost / KWH	$ 0.05725
Soil mass:	600 tons		
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)

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 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 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 Cost / KWH	$ 0.05725
Soil mass:	600 tons		
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 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 <u>(Year 1)</u>**

Flushing Vol:	109 m3	Power Consumption in:	KW
Soil mass:	600 tons	Cost / KWH	$ 0.05725
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	$ -	$ 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)

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 <u>(Year 1)</u>**

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)

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)

$ 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 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

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APPENDIX F

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 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	$ -	$ 5,464	$ -	$ 10,928	$ 10,928			Freight (Palletizing, loading, and shipping of equipmemt)
							$ 17,928	**Total Technology Mobilization 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	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 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)

Units	No of units	Unit labor cost	Unit mat cost	Labor cost	Mat cost	Item cost	Total cost	Item description
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 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	Power Consumption in:	KW
Soil mass:	49 tons	Cost / KWH	$ 0.05725
Area:	19 m2	Note: Electrical power for UF is provided by generator.	
Project duration:	2 months		

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)

Units	No of units	Unit labor cost	Unit mat cost	Labor cost	Mat cost	Item cost	Total cost	Item description
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 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

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