

N83447.AR.000166
NAS FORT WORTH
5090.3a

DRAFT REPORT SUPPLEMENTAL REVIEW OF REMEDIAL ALTERNATIVES NAS FORT
WORTH TX
6/1/1994
ENVIRONMENTAL SCIENCE AND ENGINEERING

File: 17G
A.F.

224000



**NAVAL AIR STATION
FORT WORTH JRB
CARSWELL FIELD
TEXAS**

**ADMINISTRATIVE RECORD
COVER SHEET**

AR File Number 224

File: 17A-53
A.F. 224

224001

DRAFT REPORT

Supplemental Review of Remedial Alternatives Air Force Plant 4 and Carswell Air Force Base

Prepared for:

**U.S. Army Engineer District
Ft. Worth, Texas**

Prepared by:



**Environmental
Science &
Engineering, Inc.**

June 1994

TABLE OF CONTENTS

<u>Section</u>		<u>Page</u>
1.0	INTRODUCTION	1-1
2.0	REVIEW AND EVALUATION OF THE 1993 FEASIBILITY STUDY	2-1
2.1	<u>AIR STRIPPING</u>	2-2
2.1.1	PROCESS DESCRIPTION	2-2
2.1.2	APPLICABILITY	2-4
2.1.3	LIMITATIONS	2-4
2.1.4	PROTOTYPE INSTALLATIONS	2-4
2.1.5	RESULTS ACHIEVED	2-4
2.1.6	APPLICABILITY TO THE STUDY AREA	2-4
2.2	<u>UV/H₂O₂ TREATMENT</u>	2-5
2.2.1	PROCESS DESCRIPTION	2-5
2.2.2	APPLICABILITY	2-9
2.2.3	LIMITATIONS	2-10
2.2.4	PROTOTYPE INSTALLATIONS	2-10
2.2.5	RESULTS ACHIEVED	2-10
2.2.6	APPLICABILITY TO THE STUDY AREA	2-11
2.3	<u>BIOREMEDIATION</u>	2-13
2.3.1	PROCESS DESCRIPTION	2-13
2.3.2	APPLICABILITY	2-14
2.3.3	LIMITATIONS	2-16
2.3.4	PROTOTYPE INSTALLATIONS	2-17
2.3.5	RESULTS ACHIEVED	2-17
2.3.6	APPLICABILITY TO THE STUDY AREA	2-18
2.4	<u>DENSE, NON-AQUEOUS PHASE LIQUID RECOVERY</u>	2-19
2.4.1	PROCESS DESCRIPTION	2-19
2.4.2	APPLICABILITY	2-20
2.4.3	LIMITATIONS	2-20
2.4.4	PROTOTYPE INSTALLATIONS	2-22
2.4.5	RESULTS ACHIEVED	2-22
2.4.6	APPLICABILITY TO THE STUDY AREA	2-23

TABLE OF CONTENTS
(Continued, Page 2 of 4)

<u>Section</u>		<u>Page</u>
3.0	REVIEW AND EVALUATION OF ADDITIONAL TECHNOLOGIES	3-1
3.1	<u>IN-SITU</u> BIOREMEDIATION	3-1
3.1.1	PROCESS DESCRIPTION	3-1
3.1.2	APPLICABILITY	3-3
3.1.3	LIMITATIONS	3-3
3.1.4	PROTOTYPE/PRODUCTION INSTALLATIONS	3-4
3.1.5	RESULTS ACHIEVED	3-4
3.1.6	APPLICABILITY TO THE STUDY AREA	3-4
3.2	<u>METAL-ENHANCED IN-SITU DEGRADATION</u>	3-5
3.2.1	PROCESS DESCRIPTION	3-5
3.2.2	APPLICABILITY	3-6
3.2.3	LIMITATIONS	3-6
3.2.4	PROTOTYPE/PRODUCTION INSTALLATIONS	3-6
3.2.5	RESULTS ACHIEVED	3-8
3.2.6	APPLICABILITY TO THE STUDY AREA	3-8
3.3	<u>HORIZONTAL WELL AIR SPARGING</u>	3-8
3.3.1	PROCESS DESCRIPTION	3-8
3.3.2	APPLICABILITY	3-11
3.3.3	LIMITATIONS	3-11
3.3.4	PROTOTYPE INSTALLATIONS	3-11
3.3.5	RESULTS ACHIEVED	3-12
3.3.6	APPLICABILITY TO THE STUDY AREA	3-12
	3.3.6.1 <u>Horizontal Well Air Sparging as Performed at SRS</u>	3-13
	3.3.6.2 <u>Modified Air Sparging Using Interception Trench</u>	3-14
3.4	<u>HORIZONTAL WELL BIO-SPARGING</u>	3-15
3.4.1	PROCESS DESCRIPTION	3-15
3.4.2	APPLICABILITY	3-19
3.4.3	LIMITATIONS	3-19

TABLE OF CONTENTS
(Continued, Page 3 of 4)

<u>Section</u>	<u>Page</u>	
3.4.4	PROTOTYPE INSTALLATIONS	3-20
3.4.5	RESULTS ACHIEVED	3-21
3.4.6	APPLICABILITY TO THE STUDY AREA	3-21
3.5	<u>TITANIUM DIOXIDE PHOTOCATALYTIC OXIDATION</u>	3-22
3.5.1	PROCESS DESCRIPTION	3-22
3.5.2	APPLICABILITY	3-24
3.5.3	LIMITATIONS	3-26
3.5.4	PROTOTYPE INSTALLATIONS	3-26
3.5.5	RESULTS ACHIEVED	3-26
3.5.6	APPLICABILITY TO THE STUDY AREA	3-27
3.6	<u>TWO-STAGE METHANOTROPHIC BIODEGRADATION</u>	3-29
3.6.1	PROCESS DESCRIPTION	3-31
3.6.2	APPLICABILITY	3-31
3.6.3	LIMITATIONS	3-31
3.6.4	PROTOTYPE INSTALLATIONS	3-31
3.6.5	RESULTS ACHIEVED	3-31
3.6.6	APPLICABILITY TO THE STUDY AREA	3-31
3.7	<u>HIGH-ENERGY ELECTRON BEAM IRRADIATION</u>	3-32
3.7.1	PROCESS DESCRIPTION	3-32
3.7.2	APPLICABILITY	3-34
3.7.3	LIMITATIONS	3-34
3.7.4	PROTOTYPE INSTALLATIONS	3-34
3.7.5	RESULTS ACHIEVED	3-35
3.7.6	APPLICABILITY TO THE STUDY AREA	3-35
3.8	<u>ULTRASONIC DETOXIFICATION</u>	3-35
3.8.1	PROCESS DESCRIPTION	3-35
3.8.2	APPLICABILITY	3-36
3.8.3	LIMITATIONS	3-36
3.8.4	PROTOTYPE INSTALLATIONS	3-38
3.8.5	RESULTS ACHIEVED	3-38
3.8.6	APPLICABILITY TO THE STUDY AREA	3-38

TABLE OF CONTENTS
(Continued, Page 4 of 4)

<u>Section</u>	<u>Page</u>
3.9 <u>PARTITIONING TRACER TESTING</u>	3-39
3.9.1 PROCESS DESCRIPTION	3-39
3.9.2 APPLICABILITY	3-45
3.9.3 LIMITATIONS	3-45
3.9.4 PROTOTYPE INSTALLATIONS	3-46
3.9.5 RESULTS ACHIEVED	3-46
3.9.6 APPLICABILITY TO THE STUDY AREA	3-46
4.0 CONCLUSIONS	4-1
APPENDICES	
APPENDIX A--TRIP REPORTS	

LIST OF TABLES

<u>Table</u>		<u>Page</u>
2-1	Cost Estimate, Air Stripping Alternative	2-6
2-2	Cost Estimate, Oxidation by Hydrogen Peroxide with UV Radiation	2-12
3-1	Cost Estimate, Horizontal Well Air Sparging Alternative with Permeable <u>In-Situ</u> Barrier	3-16
3-2	Cost Estimate, Horizontal Well Bio-Sparging Alternative	3-23
3-3	Cost Estimate, TiO ₂ with UV Radiation	3-28
4-1	Technology Summary Table	4-3

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
2-1	Schematic of the Air Stripping Process AFP4 and CAFB, Fort Worth, Texas	2-3
2-2	Schematic of the UV Light/H ₂ O ₂ Process AFP4 and CAFB, Fort Worth, Texas	2-8
2-3	Schematic of the Biological Treatment Process, AFP4 and CAFB, Fort Worth, Texas	2-15
2-4	Schematic of a SEAR Operation Showing a Single Surfactant Injection Well and a Single Withdrawal Well, AFP4 and CAFB, Fort Worth, Texas	2-21
2-5	Effluent Concentration of PCE from Borden Cell	2-24
3-1	Schematic of the <u>In-Situ</u> Bioremediation Process, AFP4 and CAFB, Fort Worth, Texas	3-2
3-2	Schematic of the Metal-Enhanced <u>In-Situ</u> Degradation Process, AFP4 and CAFB, Fort Worth, Texas	3-7
3-3	Schematic of the Horizontal Well Air Sparging Process, AFP4 and CAFB, Fort Worth, Texas	3-10
3-4	Schematic of the Horizontal Well Bio-Sparging Process, AFP4 and CAFB, Fort Worth, Texas	3-17
3-5	Schematic of the TiO ₂ Photocatalytic Oxidation Process, AFP4 and CAFB, Fort Worth, Texas	3-25
3-6	Schematic of the Two-Stage Methanotrophic Biodegradation Process, AFP4 and CAFB, Fort Worth, Texas	3-30
3-7	Schematic of the High Energy Electron Beam Irradiation Process, AFP4 and CAFB, Ft. Worth, Texas	3-30

LIST OF FIGURES
(Continued, Page 2 of 2)

<u>Figure</u>		<u>Page</u>
3-8	Schematic of the Ultrasonic-Detoxification Process, AFP4 and CAFB, Fort Worth, Texas	3-37
3-9	Production Well Tracer Response Curves Before Surfactant Remediation	3-41
3-10	Single-Well Partitioning Tracer Test, AFP4 and CAFB, Fort Worth, Texas	3-43
3-11	Potential Partitioning Configuration of Interwell Partitioning Tracer Test, AFP4 and CAFB, Fort Worth, Texas	3-44

AFB	Air Force Base
AFP4	Air Force Plant 4
ARARs	applicable or relevant and appropriate requirements
BACT	best available control technology
BTEX	benzene, toluene, ethylbenzene, and xylenes
CAFB	Carswell Air Force Base
CCl ₄	carbon tetrachloride
CFB	Canadian Forces Base
cfm	cubic feet per minute
CO ₂	carbon dioxide
DNAPL	dense, nonaqueous-phase liquid
DOE	Department of Energy
EBRF	Electron Beam Research Facility
EPA	U.S. Environmental Protection Agency
ESE	Environmental Science & Engineering, Inc.
FS	feasibility study
ft-bgs	feet below ground surface
GAC	granular activated carbon

LIST OF ACRONYMS AND ABBREVIATIONS
(Continued, Page 2 of 4)

224010

gpm	gallons per minute
H ⁺	hydrogen atom
H ₂ O ₂	hydrogen peroxide
H ₂ O ₂	hydrogen peroxide
HEBI	high-energy electron beam irradiation
ICT	insulated core transformer
Intera	Intera, Inc.
ISV	<u>in-situ</u> volatilization
K	Kelvin
km	kilometer
krad	kilorads
L	liter
lb/day	pounds per day
lb	pound
LB&D	Lorentz Barrel & Drum
LEAD	Letterkenny Army Depot
LEL	lower explosive limit

LIST OF ACRONYMS AND ABBREVIATIONS
(Continued, Page 3 of 4)

224011

Lpm	liters per minute
m	meter
MCL	maximum contaminant level
mg/L	milligrams per liter
MMO	methane monooxygenase
NAS	Naval Air Station
nm	nanometers
NPTT	NAPL-Partitioning Tracer Testing
NSF	National Science Foundation
O&M	operation and maintenance
OH ⁻	hydroxyl
ORNL	Oak Ridge National Laboratory
PCB	polychlorinated biphenyls
PCE	tetrachloroethene
PITT	partitioning interwell tracer tests
ppm	parts per million
ppmv	parts per million by volume

LIST OF ACRONYMS AND ABBREVIATIONS
(Continued, Page 4 of 4)

224012

RI	remedial investigation
SAD	Sacramento Army Depot
scfm	standard cubic feet per minute
SEAR	surfactant-enhanced aquifer remediation
SHARPE	Sharpe Army Depot
SITE	Superfund Innovative Technology Evaluation
SOW	Statement of Work
SRS	Savannah River Site
TCE	trichloroethene
TiO ₂	titanium dioxide
TYAFB	Tyndall Air Force Base
μg/L	microgram per liter
USACE	U.S. Army Corps of Engineers
USAF	U.S. Air Force
UT	University of Texas at Austin
UV	ultraviolet
VOC	volatile organic compound

1.0 INTRODUCTION

This draft report was prepared by Environmental Science & Engineering, Inc. (ESE) under the U.S. Army Corps of Engineers (USACE) Contract No. DACW63-93-D-001, Delivery Order No. 3, Feasibility Study and Recommendations for Remediation of the TCE Plume.

This report specifically addresses the requirements for Task 4, Supplemental Review of Remedial Alternatives. The overall goal of this report is to summarize information on all applicable technologies for the remediation of trichloroethene (TCE)-contaminated groundwater at the study area [Air Force Plant 4 (AFP4) and Carswell Air Force Base (CAFB)].

The specific requirements for Task 4 include review and evaluation of technologies presented in the remedial investigation/feasibility study (RI/FS) (Task 4A); investigation of promising technologies (Task 4B); other alternative technologies (Task 4C); and preparation of a summary report, including trip reports (Task 4D). Section 2.0 presents the requirements for Task 4.A and Sections 3.0 and 4.0 present the requirements for Tasks 4B and 4C, respectively. Sections 2.0, 3.0, and 4.0, along with Appendices A-1 through A-4, present the requirements for Task 4D.

To accomplish the objectives for Task 4, a literature search was conducted to obtain information on the current status of the innovative technologies applicable for remediation of TCE-contaminated groundwater. The survey included the following resources:

1. U.S. Environmental Protection Agency (EPA) documents and publications on innovative technologies [e.g., Supplemental Initiative Technology Evaluation (SITE) documents],
2. Databases (e.g., ATTIC, VISITT, LUIS, and Water Resources Abstracts),

3. Groundwater remediation projects implemented or potential for implementation at government installations [e.g., U.S. Air Force (USAF) bases, U.S. Army depots],
4. Groundwater remediation projects implemented or potential for implementation at industrial facilities,
5. Research publications (e.g., University of Waterloo study on the metal-enhanced in-situ degradation technology),
6. Vendor literature, and
7. Personal communications.

2.0 REVIEW AND EVALUATION OF THE 1993 FEASIBILITY STUDY (FS)

The Statement of Work (SOW) for Task 4A requires: (1) a review of the remediation technologies considered in the 1993 FS (Rust Geotech, 1993), and (2) a review of the recent, new, and/or evolving technologies not considered in the 1993 FS. This section presents the review of the remediation technologies evaluated in the 1993 FS. FS technologies are evaluated to determine if they are still applicable, based on new findings identified since publication of the FS in October 1993, as presented in the report Characterization of the TCE Plume (ESE, 1994).

The four FS technologies revisited in this report are as follows:

1. Physical treatment using air stripping,
2. Chemical treatment using ultraviolet/hydrogen peroxide (UV/H₂O₂);
3. Biological treatment using aboveground biological reactors; and
4. Enhanced dense, nonaqueous-phase liquid (DNAPL) recovery using surfactants.

In the 1993 FS, air stripping, UV/H₂O₂, and biological treatment technologies were considered applicable for groundwater remediation at the study area. DNAPL recovery using surfactants was considered an innovative technology for application to the TCE recovery at the study area.

Each of these four technologies were evaluated against the following criteria, as required by the SOW:

1. Process or methodology description,
2. Applicability,
3. Limitations,
4. Prototype installations,
5. Results achieved, and
6. Applicability to the study area.

2.1 AIR STRIPPING

2.1.1 PROCESS DESCRIPTION

Air stripping is a mass-transfer process in which a liquid containing volatile compounds is brought into contact with air, resulting in an exchange of gases between the air and water. Generally, the most efficient type of air stripping is accomplished in a packed tower equipped with an inlet blower. An alternative arrangement uses an induced-draft blower on the tower exhaust, increasing volatilization rates at the expense of reduced blower efficiency. The stripping tower consists of a cylindrical structural shell or tower filled with inert packing material that increases the surface area for gas-liquid contact and fans to force (or draw) air up through the tower while water trickles down the tower over the packing material.

Packed towers are of two basic types: counter-current and cross-flow towers. In counter-current towers, the entire airflow enters at the base of the tower, and water enters at the top of the tower and flows through the packing to the bottom. In cross-flow towers, the air is pulled through the sides of the tower along the entire height as water enters at the top and flows downward through the packing.

In this system, groundwater pumped from the extraction wellfield would be transferred to an equalization tank designed to provide a detention time to allow for variations in groundwater pumping rates. From the equalization tank, water would be pumped to air stripping tower(s). More than one tower can be used to obtain a higher degree of removal. The air strippers can be arranged either in series or parallel, depending on the flow rates and the contaminant concentrations. The effluent from the air stripper(s) flows to a discharge holding tank for monitoring and disposal. The offgas from the air strippers can be treated by a vapor-phase granular activated carbon (GAC) unit. Figure 2-1 presents a schematic of the process.

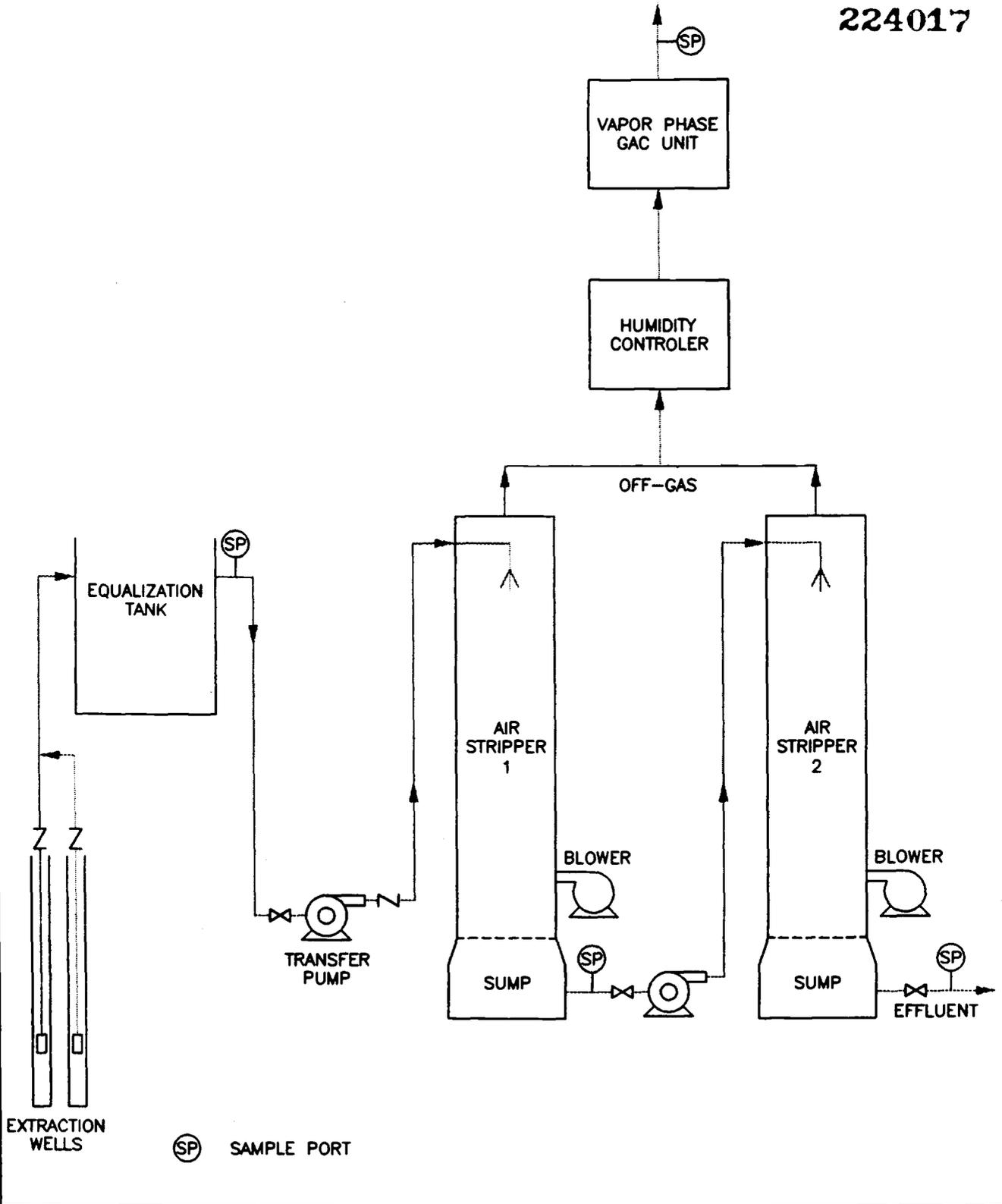


Figure 2-1
 SCHEMATIC OF THE AIR STRIPPING PROCESS
 AFP4 AND CAFB
 FORT WORTH, TEXAS
 SOURCE: ESE, 1994.



**Environmental
 Science &
 Engineering, Inc.**

2.1.2 APPLICABILITY

Packed tower air stripping treatment is a proven technology for the removal of volatile organic compounds (VOCs) from groundwater, particularly where solubilities are low.

2.1.3 LIMITATIONS

The application of the technology is limited to the removal of VOCs from groundwater. Removal rates are highly dependent on water temperature and the presence of co-solvents, such as alcohol or surfactants. Groundwater chemistry that favors formation of scale or slimes may require frequent cleaning or pretreatment. Also, if the VOC concentrations in the offgas from the air stripper exceed the federal or state standards for air emission or if air toxics regulations require control, regardless of concentration, a treatment system would be required to remove the VOCs from the offgas.

2.1.4 PROTOTYPE INSTALLATIONS

This technology is widely used for remediating VOC-contaminated groundwater and is essentially the standard to which other technologies are compared. Several full-scale treatment systems use this technology for TCE removal from groundwater.

2.1.5 RESULTS ACHIEVED

Air stripping is commonly used to remove VOCs to levels less than 1 microgram per liter ($\mu\text{g/L}$) in groundwater. TCE is particularly amenable to stripping. Typical systems used at SHARPE and Letterkenny Army Depot (LEAD) have been shown to reliably treat TCE to nondetect levels.

2.1.6 APPLICABILITY TO THE STUDY AREA

Based on the evaluation of the air stripping technology and the contaminants present in groundwater at the study area [as presented in the TCE characterization report (ESE, 1994)], this technology is considered applicable for

remediating VOC-contaminated groundwater at the study area. This technology was also considered applicable at the study area based on the evaluation presented in the 1993 FS.

A preliminary design of the air stripping treatment system was performed based on the following assumptions:

1. Groundwater flow rate of 500 gallons per minute (gpm),
2. Influent TCE concentration of 2.7 milligrams per liter (mg/L),
3. Targeted effluent concentration of 3.0 $\mu\text{g/L}$, and
4. Thirty years of treatment.

A cost estimate for the remediation of TCE-contaminated groundwater using air stripping technology is presented in Table 2-1. The cost estimate does not include the costs for buildings and the extraction wellfield. As shown in Table 2-1, major items of the capital cost include the air stripping towers, offgas treatment unit, equalization tank, and the transfer pumps. Major items of the operation and maintenance (O&M) cost include GAC replacement/reactivation and the labor costs. The estimated capital and annual O&M costs are \$124,000 and \$91,000, respectively.

2.2 UV/H₂O₂ TREATMENT

2.2.1 PROCESS DESCRIPTION

The UV/H₂O₂ process combines UV light and H₂O₂ to photo-oxidize TCE in groundwater into carbon dioxide (CO₂), water, and salts; the process does not yield air emissions or residual waste products. The primary reaction mechanism in this process involves generating hydroxyl radicals and oxidizing the contaminants present in water by UV light and H₂O₂.

The UV/H₂O₂ treatment system consists of three stages: the influent stage, the oxidation stage, and the effluent stage. In Stage I, the influent stage, H₂O₂ is injected into the influent line conveying untreated groundwater prior to an

TABLE 2.1		Date Prepared: 06/13/94							
COST ESTIMATE		Sheet 1 of 1							
Project: AFP4		AIRSTRIPPING ALTERNATIVE 224020							
A/E: ESE (3932033G-0420-3130)		Q = 500gpm, Influent Conc. = 2.7 mg/l, Effluent Conc = 3.0 µg/l							
Drawing No.		Estimator: J&P	Checked By: Reviewed By:						
Item No.	Description	Quantity		Labor & Equipment		Material		TOTAL COST	
		No. Units	Unit Meas.	Per Unit	Total	Per Unit	Total		
PROJECT SUMMARY									
I	CAPITAL COSTS								
1.	Treatment system Pad (60'X80'X0.5') including concrete, compaction, labor and equipment	89	CY	\$9.37	\$833	\$60.50	\$5,378	\$6,211	
A.	6" Curb	280	LF	\$2.20	\$616.00	\$3.10	\$868.00	\$1,484	
B.	Steel Reinforcement (#5 @ 12 each way)	5	TN	\$200	\$1,002	\$860	\$4,310	\$5,312	
2.	Equalization Tank (15,000 gal Belco, 12ft d X 18ft Straight Sidewall, Vertical dome top, flat bottom fiberglass. Includes 6in Gussetted flanges, gooseneck vent, 18 in side manway, hold down lugs, lifting lugs.)	1	ls	\$10,027	\$10,027			\$10,027	
TREATMENT SYSTEM									
1.	Air Stripping Tower (A.R.T. 3ftd X 27ft High) w/ 150 ft3 of 2in Jaeger Tripacks, mist eliminator and influent plumbing	2	ea	\$19,500				\$39,000	
A.	Transfer Pump (Gorman-Rupp model 84A3-B with 15 hp motor)	2	ea	\$4,693				\$9,387	
B.	Nozzle (Lechler model 485.756.32.06 Bronze Full Cone)	2	ea	\$680				\$1,360	
C.	Blower (Hartzell Series 031-129C Centrifugal Fan w/ adjustable Drive and 2 hp motor)	2	ea	\$1,600				\$3,200	
OFFGAS TREATMENT									
1.	Vapor Phase GAC Offgas Treatment (CarbonAir, Model GPC 70 w/ 10,000 lb Carbon @ 1.50/lb)	1	ea	\$35,000				\$35,000	
A.	Control Panel	1	ea	\$7,000				\$7,000	
B.	In-line Heater (CarbonAir 32kw w/ disconnect, contactor, air-pressure switch, thermostat w/ capillary tube)	1	ea	\$5,642				\$5,642	
ANNUAL OPERATION AND MAINTAINANCE COSTS									
1.	Carbon Reactivation (4 Changouts / year 10,000 lb capacity)	40000	lb			\$0.60		\$24,000	
2.	Power	317647	kwhr			\$0.06	\$19,071	\$19,071	
3.	Equipment replacement & Maintenance (5% of installed capital)	1	LS					\$8,335	
4.	Labor (2 hrs per day)	730	hrs	\$45.00	\$32,850			\$32,850	
5.	Monitoring (Sample/Analysis by EPA Method 8010)								
A.	Sample Cost (3 Samples + 1 Trip Blank Monthly)	48	ea	\$125.00	\$6,000			\$6,000	
B.	Sample kit (1 kit Monthly)	12	ea	\$35.00	\$420			\$420	
								Annual O&M	\$90,676
								PV of O&M (30 yrs @ 5%)	\$1,393,905
								Installed Capital	\$123,623
								Contingency (25% of Capital)	\$30,906
								Engineering (15% of Capital)	\$18,543
								O&P (12% of Capital)	\$14,835
								TOTAL COST	\$1,581,811

Note: 1) Tank, Airstripper, Offgas System costs obtained from vendor.
 2) Concrete Slab cost estimated from Means 1994.
 3) Lab cost obtained from ESE lab
 4) No Pretreatment, wellfield extraction, or piping costs included.
 Source: ESE, 1994

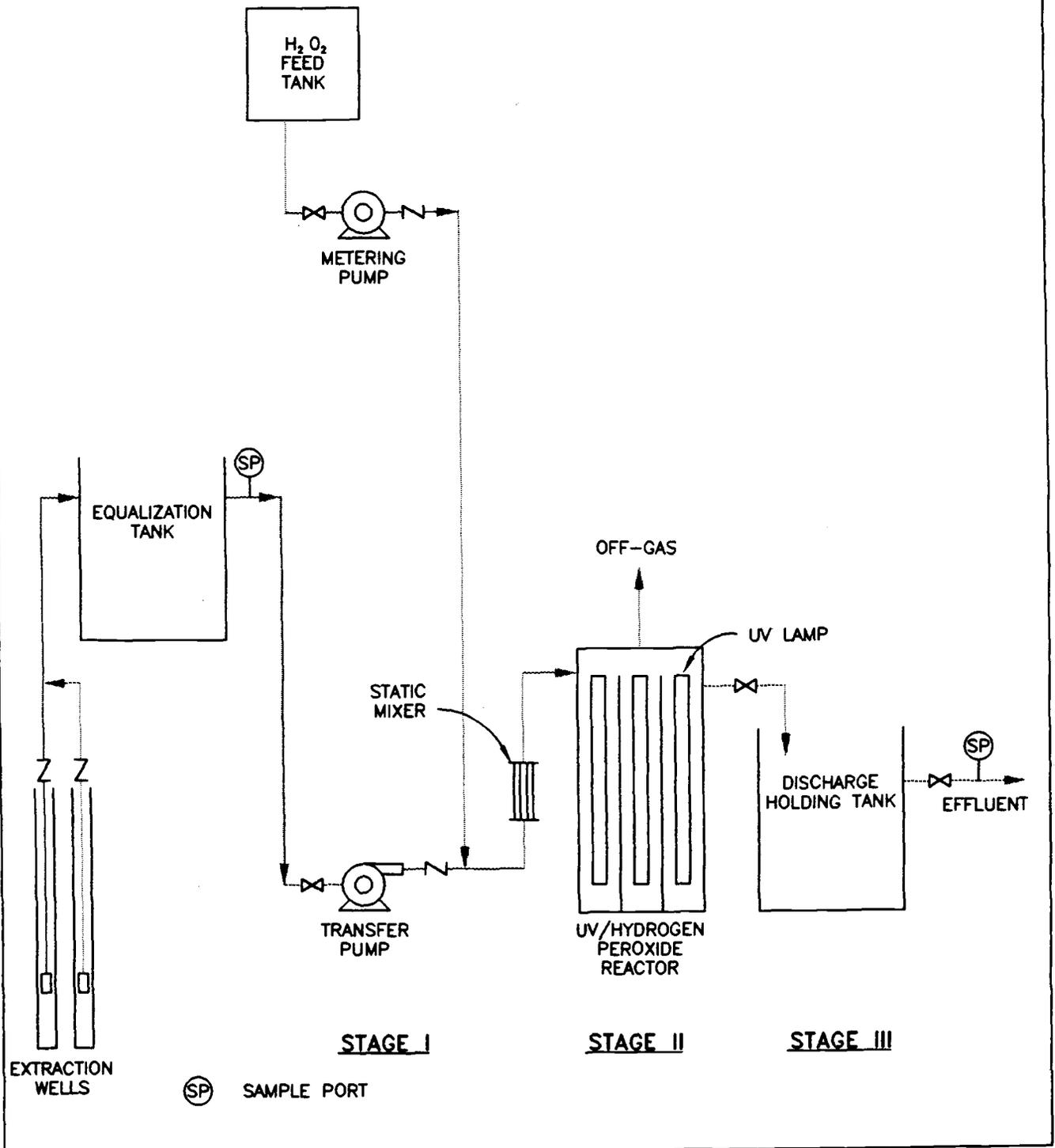
in-line static mixer. The water and H_2O_2 mixture then flows through the reactor at a predetermined rate to ensure complete oxidation of the groundwater contaminants.

In Stage II, the oxidation stage, the contaminants in the reactor are oxidized to CO_2 , water, and small amounts of chloride ions. The reactor is divided into several chambers; each chamber is equipped with high-powered UV lamps covered by quartz sheaths. The number of lamps is dependent on the unit's capacity. In the reactor, the UV light activates the H_2O_2 to form oxidizing hydroxyl radicals. The hydroxyl radicals oxidize the chlorinated organic molecules, breaking them down into their molecular components. The hydroxyl radicals then oxidize such fractions to CO_2 , water, and small amounts of chloride ions.

In Stage III, effluent from the reactor flows to a discharge holding tank. Figure 2-2 presents a schematic of the process. As depicted in the figure, the major components of the treatment process include the equalization tank, the oxidation unit, and the discharge holding tank. The groundwater may require pretreatment under some conditions. Typical forms of pretreatment that may be required include removal of suspended solids, free-phase oil and grease, and iron.

Like other chemical oxidation mechanisms, the UV/ H_2O_2 process depends on several reaction conditions that can affect system performance and cost. Some process variables are inherent to the properties of the contaminated water, but other process variables can be controlled by treatment system design and operation. Variables related to the contaminated groundwater include the following:

1. Type and concentration of organic contaminant,
2. Light transmittance of the water,
3. Type of the dissolved solids, and
4. Concentration of the dissolved solids.



Jun 21, 1994 - 10:32:03

Figure 2-2
 SCHEMATIC OF THE UV LIGHT/ H_2O_2 PROCESS
 AFP4 AND CAFB
 FORT WORTH, TEXAS
 SOURCE: ESE, 1994.



**Environmental
 Science &
 Engineering, Inc.**

Variables related to the treatment process design and operation include the following:

1. UV and H₂O₂ dosages,
2. pH,
3. Temperature conditions, and
4. Use of catalysts.

The most important design parameter is the relative amounts of energy and H₂O₂ applied to produce sufficient hydroxyl radical concentrations for adequate contaminant destruction. The economics of the process are driven by chemical feed rate, electric power, flow rate, and percent removal of the contaminant. Residence time is not a significant variable with this technology.

An ESE engineer conducted a site visit to a full-scale UV/H₂O₂ treatment system currently in operation at the Sacramento Army Depot (SAD). The treatment system operates at a flow rate of 350 gpm and remediates TCE-contaminated groundwater from an influent concentration of approximately 100 µg/L to an effluent concentration of 5 µg/L. Details of the site visit are presented in the trip report (Appendix A-2).

2.2.2 APPLICABILITY

The UV/H₂O₂ process can treat a broad range of groundwater contaminants. This technology is particularly effective for chloroalkenes such as TCE, tetrachloroethene (PCE), and vinyl chloride and has shown to be effective, especially in reaching parts-per-billion effluent limits. The process converts hydrocarbon contaminants to CO₂, water, and small amounts of chloride ions without air emissions or residual waste products. H₂O₂ is easy to handle and does not form undesirable byproducts common to other oxidants.

2.2.3 LIMITATIONS

The UV/H₂O₂ system may require pretreatment for the removal of iron, oil and grease, and suspended solids. Regular equipment maintenance is necessary to keep the quartz sheaths clean since the organics and metals in the groundwater can foul the UV lamps and decrease their effectiveness to degrade the organic compounds. Pretreatment may be necessary under some conditions (e.g., removal of suspended solids, oil and grease, and iron).

2.2.4 PROTOTYPE INSTALLATIONS

Ultrox International demonstrated a field study using this technology at the Lorentz Barrel & Drum (LB&D) Superfund site in San Jose, California (Remediation, 1991). Under the Superfund Innovative Technology Evaluation (SITE) program, PRC Environmental Management, Inc. and EPA monitored the system's performance. The system consisted of six baffled compartments, with each compartment consisting of four 65-watt UV lamps.

A full-scale UV/H₂O₂ treatment system (350 gpm) is in operation at SAD, California, and remediates TCE-contaminated groundwater from an influent concentration of 100 µg/L to less than 5 µg/L. At a large chemical facility in the Pacific Northwest, the UV/H₂O₂ process was used to remediate TCE-contaminated groundwater at 70 gpm (Bernardin, 1991).

2.2.5 RESULTS ACHIEVED

The field studies at the San Jose site revealed that the UV/H₂O₂ system is particularly effective in breaking down unsaturated aliphatics (e.g., TCE and vinyl chloride). TCE destruction efficiencies greater than 90 percent were achieved. The maximum TCE concentration detected in groundwater at the San Jose site was 920 µg/L.

The full-scale treatment system at SAD has been in operation for the past 3 years and has been successfully remediating TCE-contaminated groundwater.

Destruction efficiencies for TCE in excess of 95 percent are achieved with TCE effluent concentrations to less than 5 $\mu\text{g/L}$.

At the referenced chemical facility in the Pacific Northwest, the influent and effluent concentrations of TCE were 1,400 $\mu\text{g/L}$ and less than 1 $\mu\text{g/L}$, respectively.

2.2.6 APPLICABILITY TO THE STUDY AREA

Based on the evaluation of the UV/H₂O₂ technology and the contaminants present in groundwater at the study area [as presented in the TCE characterization report (ESE, 1994)], this technology is considered applicable for groundwater remediation at the study area. This technology was also considered applicable at the study area based on the evaluation presented in the 1993 FS.

A cost estimate for the remediation of TCE-contaminated groundwater is presented in Table 2-2. The following assumptions are made in the cost estimate:

1. Groundwater flow rate of 500 gpm,
2. Influent TCE concentration of 2.7 mg/L,
3. Targeted effluent concentration of 3.0 $\mu\text{g/L}$,
4. No required groundwater pretreatment, and
5. Thirty-year separation period.

As shown in Table 2-2, the major components of the capital cost include the UV H₂O₂ system, equalization tank, and the transfer pumps. The major components of the O&M cost include the power consumption and the chemical cost. The estimated capital and annual O&M costs are \$280,000 and \$170,000, respectively.

TABLE 2.2

COST ESTIMATE

Project: AFP4

OXIDATION BY HYDROGEN PEROXIDE WITH UV RADIATION
224026

A/E: ESE (3932033G-0420-3130)

Q = 500gpm, Influent Conc. = 2.7 mg/l, Effluent Conc = 3.0 ug/l

Drawing No.

Estimator: JMF

Checked By:

Reviewed By:

Item No.	Description	Quantity		Labor & Equipment		Material		TOTAL COST
		No. Units	Unit Meas.	Per Unit	Total	Per Unit	Total	
PROJECT SUMMARY								
I	CAPITAL COSTS							
1.	Treatment system Pad (60'X80'X0.5') including concrete, compaction, labor and equipment	89	CY	\$9.37	\$833	\$61	\$5,378	\$6,211
A.	6" Curb	280	LF	\$2.20	\$616.00	\$3.10	\$868.00	\$1,484
B.	Steel Reinforcement (#5 @ 12 each way)	5	TN	\$200	\$1,002	\$860	\$4,310	\$5,312
2.	Equalization Tank (15,000 gal Belco, 12ft d X 18ft Straight Sidewall, Vertical dome top, flat bottom fiberglass. Includes 6in Gussetted flanges, gooseneck vent, 18 in side manway, hold down lugs, lifting lugs.)	1	ea	\$10,027	\$10,027			\$10,027
B.	UV Peroxide System (Peroxidation, model E-180 with Model PM-2500B Hydrogen Peroxide Storage Feed Module)	1	ea	\$250,000				\$250,000
C.	Installation/Startup	1	LS	\$10,000				\$10,000
II	ANNUAL OPERATION AND MAINTAINANCE COSTS							
1.	Power	1E+06	kwhr			0.06	\$80,000	\$80,000
2.	Equipment Maintenance and Replacement (8% of Installed Capital)	1	LS				\$20,000	\$20,000
3.	Hydrogen Peroxide (50% Soln)	46500	lb			0.65	\$30,225	\$30,225
A.	Hydrogen Peroxide Storage and Handling (10% of H2O2 Cost)	1	LS				\$3,023	\$3,023
4.	Labor (2 hrs per day)	730	hrs	\$45.00	\$32,850			\$32,850
5.	Monitoring (Sample/Analysis by EPA Method 8010)							
A.	Sample Cost (2 Samples + 1 Trip Blank Monthly)	36	ea	\$125.00	\$4,500			\$4,500
B.	Sample kit (1 kit Monthly)	12	ea	\$35.00	\$420			\$420
				Annual O&M				\$171,018
				PV of O&M (30 yrs @ 5%)				\$2,628,962
				Installed Capital				\$283,034
				Contingency (25% of Capital)				\$70,758
				Engineering (15% of Capital)				\$42,455
				O&P (12% of Capital)				\$33,964
				TOTAL COST				\$3,059,174

Note: 1) Tank, H2O2, Peroxide System obtained from vendor.
 2) Concrete Slab cost estimated from Means 1994.
 3) Lab cost obtained from ESE lab
 4) No Pretreatment, wellfield extraction, or piping costs included.
 Source: ESE, 1994

2.3 BIOREMEDIATION

2.3.1 PROCESS DESCRIPTION

The objective of biological treatment (bioremediation) is to remove organic constituents from the waste stream via microbial degradation. The most prevalent form of biological treatment is aerobic (i.e., in the presence of oxygen); however, anaerobic treatment systems are available. There are several biological treatment processes that are applicable to the treatment of aqueous wastes, such as the following:

1. Conventional activated sludge,
2. Extended aeration,
3. Contact stabilization,
4. Rotating biological contactors, and
5. Biological reactors.

There are three main types of biological reactors:

1. Suspended growth reactors,
2. Fixed film reactors, and
3. Hybrid reactors.

In suspended growth reactors, bacteria grown suspended in water is mixed (usually by aeration) with the wastewater. A clarifier follows the process to settle out heavier bacteria.

In fixed film reactors, high surface area packing is submerged in a tank of water, or contaminated water is trickled over the packing. Bacteria which naturally attach to any surface, attach to and grow on the packing. Contaminated water is passed through the system and the bacteria metabolize the contaminants as contact is made.

The fluidized bed reactor (one type of hybrid reactor) is a high-rate biological system that is somewhat different from the typical fixed film suspended growth

systems. Generally, wastewater is passed upward through a reaction vessel that is partially filled with fine-grained media. The wastewater velocity through the reaction vessel is sufficient to fluidize the media bed. A biological mass grows on the media surface and effectively metabolizes the organics flowing through the system. The fluidized bed biological reactor system combines features of activated sludge and trickling filters in one process.

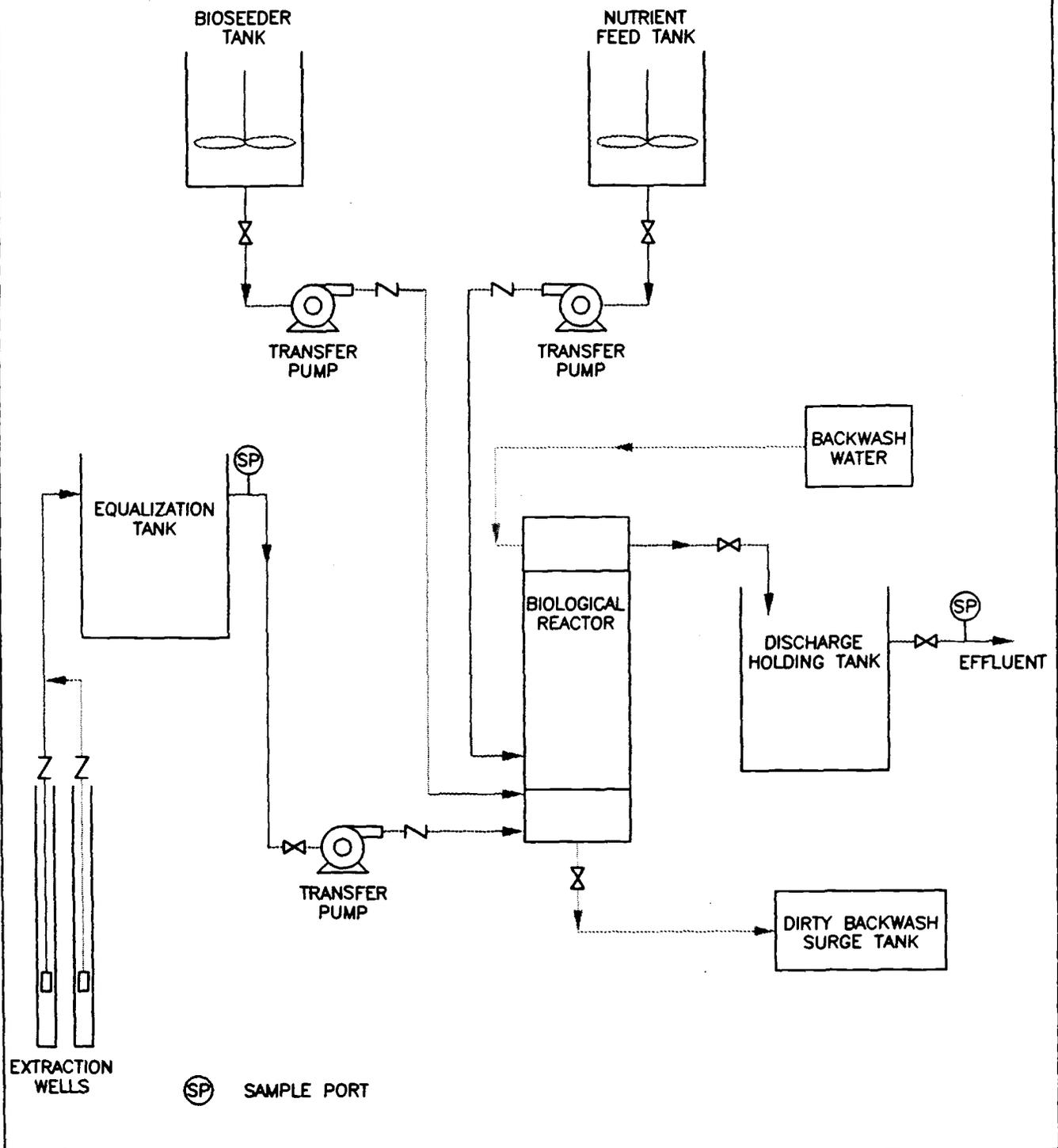
The components of the bioremediation system include biological reactor(s), an equalization tank, a nutrient tank(s), a bioseeder tank, a discharge holding tank, a dirty backwash surge tank, and transfer pumps. More than one reactor can be used in series to obtain a higher degree of removal or in parallel to accommodate higher flows.

In this system, groundwater pumped from the extraction wellfield would be pumped to an equalization tank designed to dampen out variations in groundwater pumping rates. From the equalization tank, water would be pumped to biological reactor(s), which, as previously mentioned, can be arranged either in series or parallel depending on the flow rates and the contaminant concentrations. The biological reactor is provided with a continuous inoculation with suitable organisms from a bioseeder, and nutrients are pumped from chemical feed tanks, together enhancing the growth and development of the microbial population in the reactor. The effluent from the biological reactor(s) flows to a discharge holding tank for monitoring and disposal, and to allow for recirculation if discharge limits are not met.

Figure 2-3 presents a schematic of the process.

2.3.2 APPLICABILITY

The fixed film and fluidized bed bioremediation treatment technologies are applicable for the treatment and removal of petroleum hydrocarbons, non-chlorinated solvents, and wood treating compounds. For applications to chlorinated compounds, biological remediation systems are not known to reliably



Jun 10, 1994 - 08:26:20

Figure 2-3
 SCHEMATIC OF THE BIOLOGICAL
 TREATMENT PROCESS
 AFP4 AND CAFB, FORT WORTH, TEXAS
 SOURCE: ESE, 1994.



**Environmental
 Science &
 Engineering, Inc.**

produce high removal efficiencies. This is partially due to the chemical structure of the chlorinated compound and the toxic breakdown products that are sometimes generated from the parent compound. Therefore, further treatment of the effluent may be required before disposal of treated wastewater. A variation of this technology is described in Section 3.2, wherein refractory compounds can be destroyed as a side reaction to metabolism of methane.

2.3.3 LIMITATIONS

Biological reactors require stable operating conditions. Abrupt changes in waste stream characteristics can generate shock loadings to the biomass. The maintenance of consistent, favorable reactor conditions is crucial for consistent treatment of the waste stream. The efficiency of the treatment system is dependent on a number of factors, which must be accurately predicted or controlled, including the following:

1. Dissolved oxygen,
2. pH,
3. Nutrients,
4. Alkalinity,
5. Level of suspended solids,
6. Liquid retention times of 2 to 5 hours,
7. Temperature,
8. Influent flow rate,
9. Presence of other contaminants in the waste stream, and
10. Solubility of specific contaminants.

Some of the limitations and restrictions of the biological treatment technology are as follows:

1. Residual degradation products can be as toxic or more toxic than the parent compounds;

2. Lower solubility contaminants in the waste stream are more difficult to biodegrade (only a factor if undissolved DNAPLs are drawn into the recovery wells);
3. High concentrations of highly chlorinated organics and inorganic salts can be highly toxic to microorganisms;
4. pH outside the range of 4.5 to 7.5 inhibits aerobic biological activity; and
5. Technology is site specific, requiring treatability tests (e.g., bench scale, pilot-scale tests) to determine applicability.

In addition, settled sludge and/or excess biomass residuals may contain elevated levels of toxic organics or heavy metals. The sludge will require dewatering and possibly offsite disposal. The generation of undesirable odors or the driving off of VOCs from aeration tanks may necessitate the use of special venting and filtering procedures for gases.

2.3.4 PROTOTYPE INSTALLATIONS

A pilot-scale study for this treatment technology was conducted at Tinker Air Force Base (AFB), Oklahoma (EPA, 1992). Groundwater contaminated with TCE was treated by a fixed-film bioreactor. The flow rate through the bioreactor was 2 to 3 liters per minute (Lpm) with a retention time of 20 to 50 minutes. Oxygen, methane, and enzymes were added to the contaminant waste stream to support the treatment process.

A pilot-scale fluidized bed biological reactor was installed and operated at the Department of Energy (DOE) Savannah River Site (SRS) to remove TCE in groundwater (EPA, 1992).

2.3.5 RESULTS ACHIEVED

Approximately 80 percent destruction of TCE was achieved during the Tinker AFB study; however, no information is available regarding the influent/effluent

concentrations of the wastewater. Based on this progress, a joint effort is currently underway by DOE's Oak Ridge National Laboratory (ORNL) to perform a comparison between two bioreactors capable of biodegrading TCE within a mixture of other solvents.

The results achieved from the SRS were promising. The pilot-scale evaluation identified bacteria that can aerobically degrade TCE, and PCE was isolated from native soil. Propane and methane were found to stimulate TCE and PCE degradation. Fluidized bed bioreactors, using propane or methane as a primary energy source, were 99 and 50 percent effective in reducing TCE and PCE concentrations in contaminated groundwater, respectively. However, no information is available regarding the influent/effluent concentrations of the wastewater. In addition, other wastes were also degraded when mixed wastes were used in the reactor.

2.3.6 APPLICABILITY TO THE STUDY AREA

This technology has limitations as to the TCE destruction efficiency and the stability of microorganisms. Destruction efficiencies greater than 99 percent would be required to achieve the maximum contaminant level (MCL) for TCE at the study area. Although there are several aboveground pilot-scale systems which are reported to have successfully degraded TCE over a few days of operation, none has shown to be effective over a long period of time. Further development would be required before full-scale implementation of this technology for the remediation of TCE-contaminated groundwater at the study area.

Based on the previous evaluation, this technology should not be further considered for remediating the TCE plume at the study area.

In the 1993 FS, this technology was considered applicable at the study area. However, based on evaluation of the technology presented in this section, further

development of the technology would be necessary to improve the process for the stability of the microorganisms to obtain higher TCE destruction efficiency, and operation of the system over a long time period.

A cost estimate was not prepared for this technology as it is not considered applicable at the study area.

2.4 DENSE, NON-AQUEOUS PHASE LIQUID RECOVERY

2.4.1 PROCESS DESCRIPTION

DNAPLs such as chlorinated solvents, creosote, and polychlorinated biphenyl (PCB) oils, are a common source of groundwater contamination. Chlorinated solvents (e.g., trichloroethylene, tetrachloroethylene, and 1,1,1,-trichloroethane), the most common type of DNAPL compounds, exhibit specific physical and chemical properties that together with geologic conditions influence their migration and fate in the subsurface. These properties generally include low viscosity, high volatility, weak adsorption, and densities that are greater than water. Pump-and-treat technologies can be used to contain and remove the dissolved phase plume, but removal of the immiscible phase (DNAPL) is more difficult to achieve. Source removal technologies include surfactant flushing, co-solvent flushing, water flooding, vapor extraction/air sparging, and bioremediation.

Injecting fluids increase hydraulic gradients, reduce interfacial tension, reduce DNAPL viscosity, and increase DNAPL solubility. Surfactant flushing enhances DNAPL mobility by lowering the interfacial tension between the non-aqueous phase and water, increasing the solubility of many DNAPLs by several orders of magnitude. With this removal technology, a surfactant solution is injected into the groundwater as a slug in a flooding sequence to decrease the interfacial tension between DNAPL and water by several orders of magnitude [i.e., from 20 to 50 dynes/cm to less than 0.01 dynes/cm]. The resulting decrease in interfacial tension promotes coalescence and increases the solubility of DNAPL in

water by as much as several orders of magnitude. Thus, this method enhances the recovery of DNAPL by increasing the solubility of DNAPL in groundwater.

Figure 2-4 presents a schematic of the process.

Surfactants are classified according to the chemical characteristics of their hydrophilic group and their selection is based on the properties of the surfactant group and the DNAPL properties. Some surfactants used in the oil industry include petroleum sulfonates, synthetic sulfonates, ethoxylated sulfonates, and ethoxylated alcohols (EPA, 1991). Surfactants for use in recovering TCE are currently being developed by INTERA, Inc. of Austin, Texas, in cooperation with the University of Texas at Austin.

Figure 2-4 presents a schematic of the DNAPL formation in groundwater. As shown in the figure, DNAPL migrates to the groundwater table as it is released from the ground surface. The DNAPL can sink further into the groundwater zone until encountering the top of the confining layer. Further migration is possible throughout the confining layer, through fractures and fissures, or in the case of clays, adsorption.

2.4.2 APPLICABILITY

Surfactant flushing techniques, used for enhanced oil recovery, appear to be applicable to the recovery of non-aqueous phase liquids from contaminated waste sites.

2.4.3 LIMITATIONS

The complex subsurface distribution of DNAPL is a function of geologic heterogeneities and can prevent injected fluids from making thorough contact with subsurface DNAPL. The use of enhanced DNAPL recovery techniques in the area of hazardous waste remediation is in its infancy. Most of the techniques were developed for enhanced oil recovery applications. Consequently, little

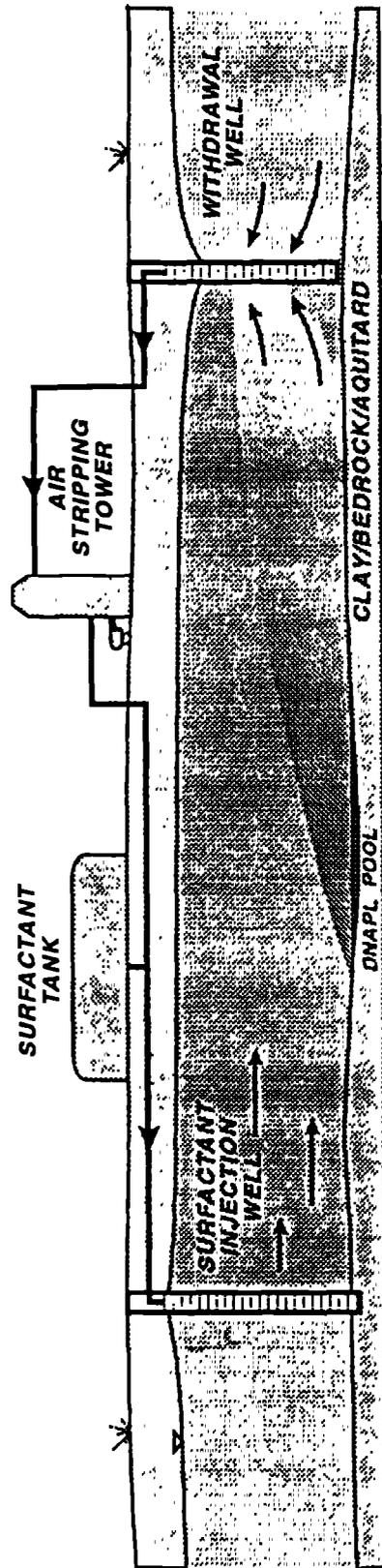


Figure 2-4
SCHEMATIC OF A SEAR OPERATION SHOWING A SINGLE
SURFACTANT INJECTION WELL AND A SINGLE WITHDRAWAL WELL
AFP4 AND CAFB, FORT WORTH, TEXAS
 SOURCE: ESE, 1994.



Environmental
 Science &
 Engineering, Inc.

information is available concerning field applications of enhanced DNAPL recovery techniques.

2.4.4 PROTOTYPE INSTALLATIONS

The surfactant flushing technique was originally applied to enhanced oil recovery; however, application of surfactants to enhance DNAPL recovery at contaminated sites is being developed. Most of the work completed to date has used laboratory columns; some tests have reached the field demonstration level but have not yielded acceptable recovery levels (Martel *et al.*, 1993).

In 1990 and 1991, a major field test of surfactant-enhanced aquifer remediation (SEAR) was undertaken by SUNY-Buffalo and the Waterloo Center for Groundwater Research (Fountain, 1992; Fountain and Hodge, 1992; Fountain and Waddell-Sheets, 1993). The test at Canadian Forces Base Research, Borden, Ontario, involved the controlled contamination of a shallow sand aquifer with 231 liters of PCE. The PCE was released to a hydraulically isolated zone of the sand aquifer created at the installation of sheet piling to create a 3 meter (m) x 3 m x 4 m deep cell. The 2 percent mixture of nonylphenol ethoxylate and a phosphate ester of an alkylphenol ethoxylate was injected in five wells on one side of the cell and extracted from five other wells on the other side of the cell. PCE concentrations were determined daily on the bulk effluent and from six sample points on each of five multi-level monitoring wells. Progress was also monitored by comparing PCE saturations in three cores taken within a few centimeters of each other, one before the start of surfactant injection, one after seven pore volumes had been injected, and one after 14 pore volumes had been injected.

2.4.5 RESULTS ACHIEVED

Field studies were conducted on DNAPL (creosote) resulting in recovery of 94 percent of the original DNAPL (EPA, 1991).

Traditional pump-and-treat was not effective in removing the PCE at Borden, Ontario; only 2 liters (L) of PCE were extracted during 6.2 pore volumes of water flooding. Subsequently, solubilization increased the contaminant concentration in the extracted water to over 4,000 parts per million (ppm) of PCE at surfactant breakthrough as compared with an aqueous solubility of 239 (mg/L). Figure 2-5 is a representation of PCE concentration as a function of pore volumes, as concluded from tests. PCE concentrations in individual multi-level samples exceeded 11,000 ppm, a more than fifty-fold increase relative to the maximum concentration in water. The results, after circulation of 16 pore volumes of fluid, indicated that residual DNAPL had been removed from virtually the entire cell (Fountain and Hodge, 1992). Fountain and Waddell-Sheets (1993) report that 62 L of PCE were extracted during 14.4 pre volumes of SEAR.

Waddell-Sheets have identified four requirements for the implementation of SEAR in granular aquifer systems: (1) the presence of DNAPL, (2) sufficiently high hydraulic conductivity (more than 10^{-5} m/s, (3) an underlying aquitard to prevent vertical migration; and (4) a clay content <5 percent by weight.

2.4.6 APPLICABILITY TO THE STUDY AREA

This innovative technology is widely used in the oil industry but application in the environmental industry for the enhancement of DNAPL recovery is still in its infancy. In the 1993 FS, this technology was considered applicable at the study area.

This technology appears promising and should be evaluated further in the Study Area FS. Due to the complex subsurface geology at the Study Area, placement and screening of wells for injection and extraction is critical to the successful implementation of this technology. This technology was considered innovative and applicable at the study area based on the evaluation in the 1993 FS.

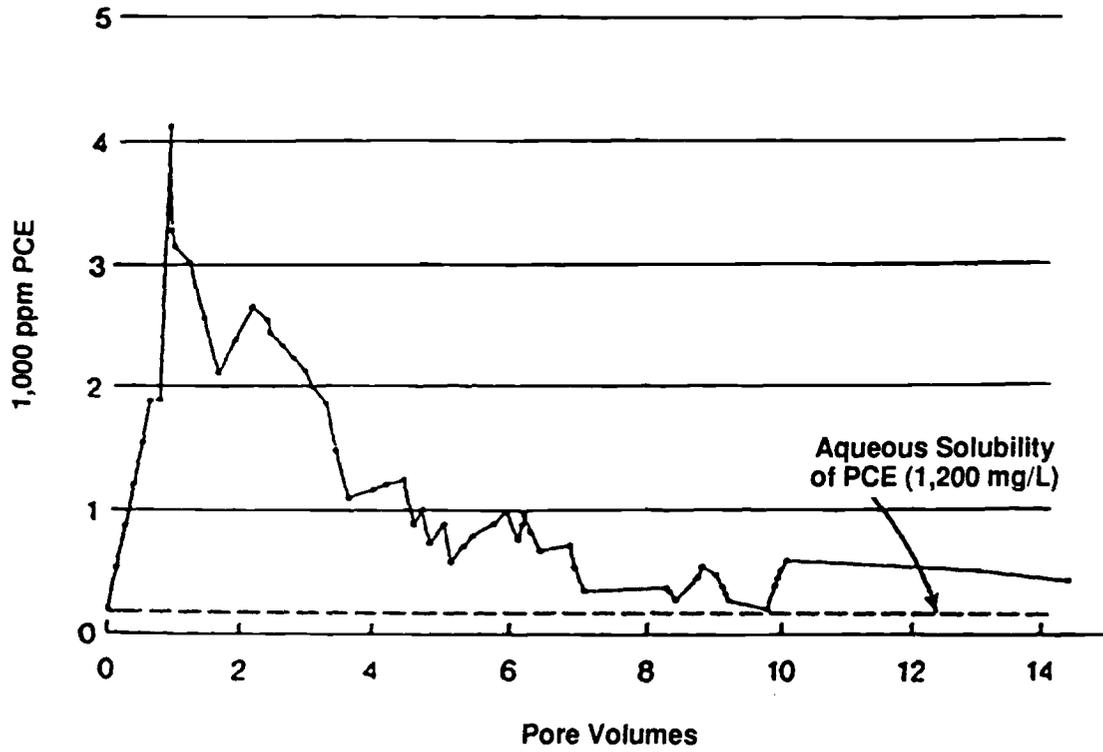


Figure 2-5
EFFLUENT CONCENTRATION OF PCE
FROM BORDEN CELL (MODIFIED AFTER
FOUNTAIN AND HODGE, 1992).

SOURCE: ESE, 1994.



Environmental
Science &
Engineering, Inc.

224039

Capital and O&M costs associated with the implementation of this technology are not available.

3.0 REVIEW AND EVALUATION OF ADDITIONAL TECHNOLOGIES

The SOW for Task 4A requires: (1) a review of the remediation technologies considered in the 1993 FS, and (2) a review of the promising technologies. This section presents the review of recent, new and/or evolving remediation technologies. Technologies described are as follows:

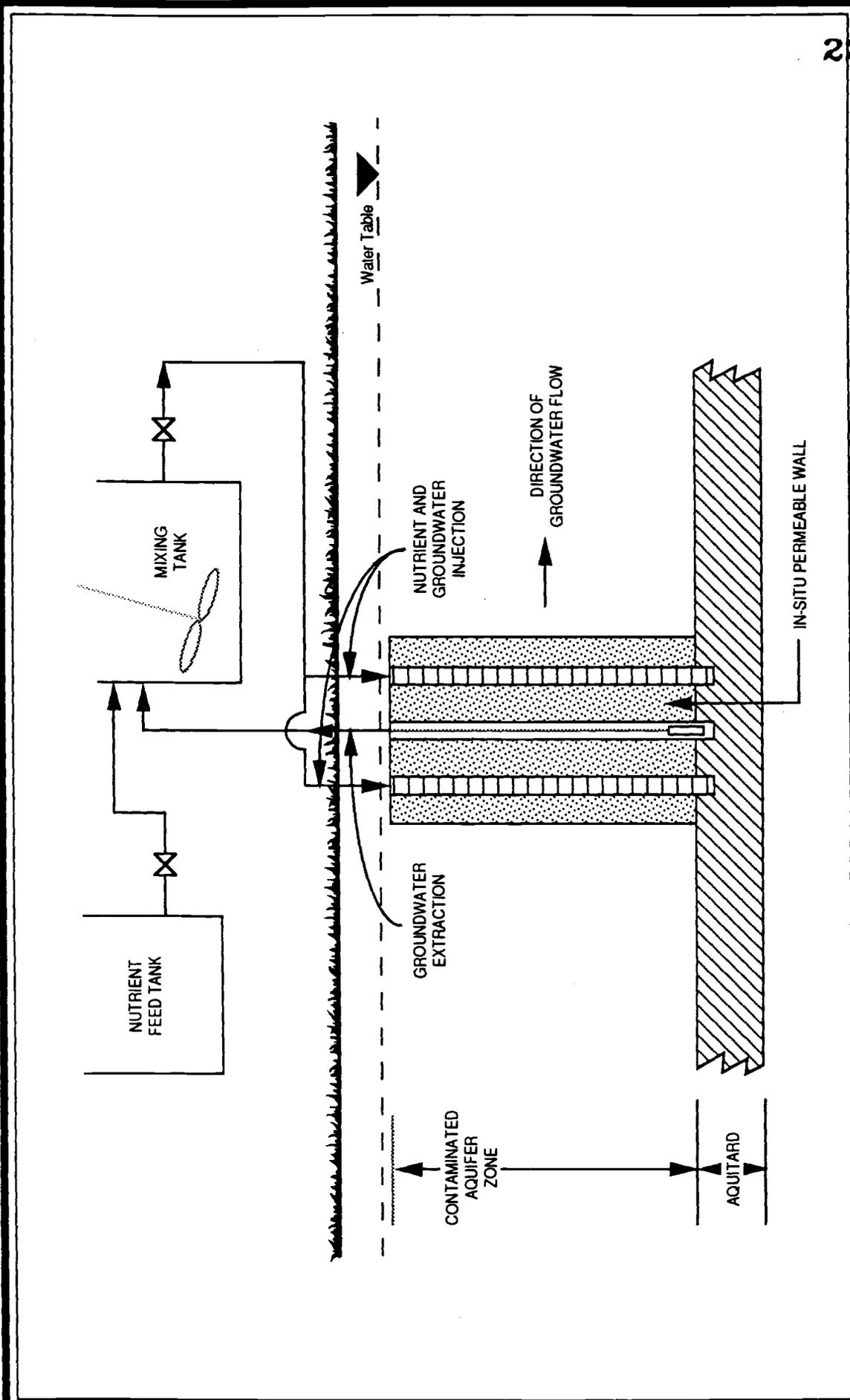
1. In-situ bioremediation,
2. Metal-enhanced in-situ degradation,
3. Horizontal well air sparging,
4. Horizontal well bio-sparging,
5. Titanium dioxide photocatalytic oxidation,
6. Two-stage methanotrophic biodegradation,
7. High-energy electron beam irradiation,
8. Ultrasonic detoxification, and
9. Partitioning tracer testing.

Each of the listed technologies presented in this section were evaluated against the same criteria applied in Section 2.0.

3.1 IN-SITU BIOREMEDIATION

3.1.1 PROCESS DESCRIPTION

An in-situ permeable barrier having a permeability substantially greater than the natural geologic material is constructed across the path of a contaminated plume. Through a series of withdrawal and injection wells, the water within the wall is removed, amended with nutrients, and reinjected. The pulse of nutrient-amended water is then carried downstream of the wall at the natural groundwater velocity. The periodic amendment of the water within the wall results in a series of pulses migrating downstream from the wall. As a result of dispersion process, the pulses mix with the contaminated water and coalesce to form a continuous zone of nutrient-amended groundwater. Figure 3-1 presents a



224041



Figure 3-1
SCHEMATIC OF THE IN-SITU BIOREMEDIATION PROCESS
AFP4 AND CAFB, FORT WORTH, TEXAS

SOURCE: UNIVERSITY OF WATERLOO, ESE.

schematic of the process. As shown in the figure, the treatment system consists of an aboveground nutrient feed system, a mixing tank, and transfer pumps.

An ESE engineer conducted a site visit to a field study of this technology at the Canadian Forces Base (CFB) Borden. Devlin and Barker (1993) conducted a field study with the University of Waterloo for the remediation of groundwater contaminated with TCE and carbon tetrachloride (CCl₄). The details of this study are presented in the trip report (Appendix A-1).

3.1.2 APPLICABILITY

In general, in-situ bioremediation is applicable to the remediation of groundwater contaminated with organic compounds, provided an effective microbial population is developed for the degradation of these organic compounds. Few organisms can achieve direct metabolism of chlorinated hydrocarbons; however, a variation of this technology is presented in Section 3.4, wherein refractory compounds can be destroyed as a side reaction to the metabolism of methane.

3.1.3 LIMITATIONS

In-situ bioremediation technology has the following limitations:

1. The sections of a plume that passed through the aquifer before the bioactive zone was established may be out of reach of the stimulated microbial populations and may have to be controlled or captured by other means;
2. After the passive wall is in place, time may be required for microbial populations to adapt to the new environmental conditions;
3. This variant of bioremediation, using an interception trench, does not address contamination in source areas and treatment duration will be similar to a pump-and-treat system;
4. Direct metabolism of chlorinated hydrocarbons such as trichloroethylene is difficult and slow (as noted in Sections 3.1.2 and 3.4, co-metabolism with methane is more promising);

5. The depth to which the permeable wall must be installed to intercept the contaminant plume for effective remediation may be technically infeasible (the interception trench must either key into an aquitard or extend a sufficient distance below the bottom of the plume); and
6. Injection wells used for bioremediation have a tendency to become fouled after a period, requiring frequent cleaning and rehabilitation.

3.1.4 PROTOTYPE/PRODUCTION INSTALLATIONS

A field evaluation of the in-situ bioremediation technology was conducted at CFB, Borden. A permeable wall 1-m thick, 4-m deep, and 4-m long was installed at the test site. Initial tests were conducted using nonreactive tracers to determine the time required to replace water with nutrients in the wall. Acetate was used to stimulate methanogenesis for the reductive dechlorination of CCl_4 and TCE within the aquifer and downstream of the permeable wall.

A site visit was conducted by an ESE engineer and the details of the visit are presented in Appendix A-1.

3.1.5 RESULTS ACHIEVED

Initial tests with nonreactive tracers showed that replacement of water in the wall every 5 weeks resulted in pulses of water that coalesced within a travel distance of 5 m from the wall. The field trials were recently completed and were successful in degrading CCl_4 to greater than 90 percent levels. However, the experiments were unsuccessful in degrading TCE. It was reported that TCE degradation in groundwater was unsuccessful and degradation rates of less than 10 percent were achieved during the prototype test.

3.1.6 APPLICABILITY TO THE STUDY AREA

Prototype tests using the in-situ remediation technology were unsuccessful in degrading TCE in groundwater. Direct metabolism of TCE by the organisms present in the demonstration was apparently too slow and incomplete to provide

effective remediation/restoration of a TCE-contaminated aquifer. The use of the interception trench may, however, have application at the study area in conjunction with other technologies such as bio-sparging. Based on this evaluation, this technology is not considered applicable for the remediation of groundwater at the study area.

A cost estimate was not prepared for this technology as it is not considered applicable at the study area.

3.2 METAL-ENHANCED IN-SITU DEGRADATION

3.2.1 PROCESS DESCRIPTION

With this technology, an in-situ permeable wall, consisting of a metal catalyst and sand, is built across the path of the contaminated plume. The chlorinated aliphatic organic compounds in the contaminated plume are degraded as it passes through the permeable wall.

The permeable wall is built by driving sheet piling to form a cell across the flow path of the contaminated groundwater plume; the cell is then filled with a mixture consisting of concrete sand and zero-valence metal (e.g., iron filings). Concrete sand is used to ensure that the wall would be more permeable to the contaminants than the surrounding geologic material. After the passive wall is installed, the sheet piling is removed, allowing the plume to pass through the wall. As the plume passes through the passive wall, the organic compounds present in the groundwater react with the metal catalyst and are degraded. To monitor the performance of the passive wall, samples are collected from several monitor wells installed upgradient and downgradient of the wall. The nature of the degradation process is reductive dechlorination and is shown by the following equation:



Figure 3-2 presents a schematic of the process. The figure shows that the contaminants are degraded as the plume passes through the permeable wall.

A field study of this technology was conducted by the University of Waterloo at CFB, Borden, for the purpose monitoring the degradation of TCE in groundwater. An ESE engineer also conducted a site visit to CFB, Borden. Details of the site visit are presented in Appendix A-1.

3.2.2 APPLICABILITY

Using this technology, several chlorinated organic compounds were successfully degraded during column tests in the laboratory (e.g., CCl_4 , hexachloroethane, tetrachloroethene, and TCE) and the effectiveness of several metals (e.g., iron, zinc, copper, brass, and aluminum) for the degradation of these compounds was also evaluated (Gillham, 1992). However, results of the field study using TCE indicated the presence of dichloroethylene as a degradation product in the downgradient plume.

3.2.3 LIMITATIONS

The effects of inorganic groundwater parameters on the reaction rate, persistence of the reaction over time, the range of compounds for which the process is applicable, and the reaction mechanism are not understood from the field study.

3.2.4 PROTOTYPE/PRODUCTION INSTALLATIONS

Based on the column study results, a field study was initiated in May 1991. A permeable wall using iron fillings and sand was built at CFB, Borden [which is approximately 120 kilometers (km) from the City of Waterloo], by the University of Waterloo to observe the degradation of TCE in groundwater (Gillham, 1993).

224046

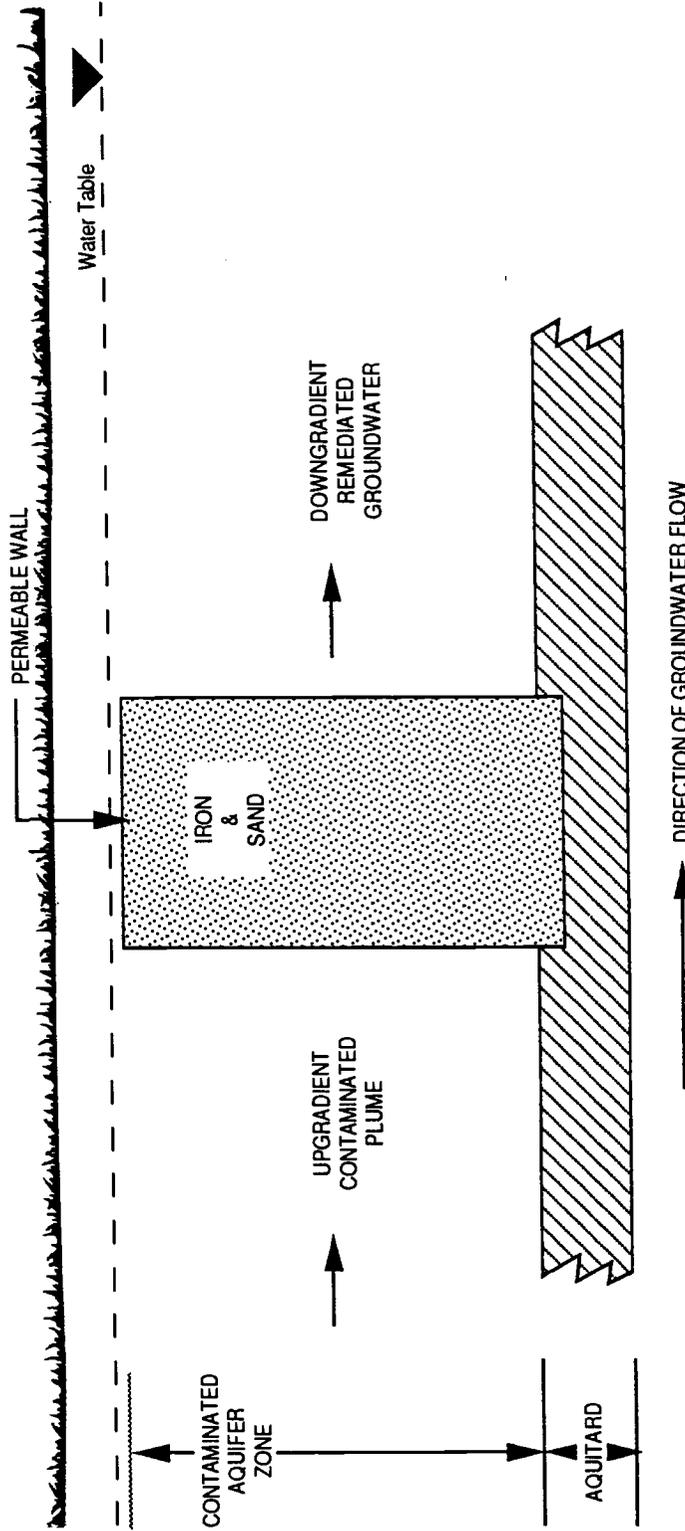


Figure 3-2
SCHEMATIC OF THE METAL-ENHANCED IN-SITU DEGRADATION PROCESS
AFP4 AND CAFB
FORT WORTH, TEXAS
 SOURCE: UNIVERSITY OF WATERLOO, ESE.

ESE
 Environmental
 Science &
 Engineering, Inc.
 A CILCORP Company

3.2.5 RESULTS ACHIEVED

The system was monitored for over a year, and during this period no evidence of a decline in the effectiveness of the permeable wall was observed. However, 1,2-dichloroethylene was detected as the degradation product of TCE in the downgradient plume. The 1,2-dichloroethylene concentrations were detected in excess of the federal MCLs.

3.2.6 APPLICABILITY TO THE STUDY AREA

Although a field test of this technology was successful in degrading TCE in groundwater at CFB Borden, the degradation may be incomplete. As a result, 1,2-dichloroethylene was detected in the downgradient plume indicating that the catalyst degradation of TCE may be incomplete. Moreover, the critical parameters including reaction rate, persistence of the reaction over time, and the reaction mechanism are not understood from the field study.

This technology appears promising; however, the mechanism of contaminant degradation is not completely understood for the development of a full-scale system. Therefore, this technology is not considered applicable for the remediation of groundwater at the study area.

A cost estimate was not prepared for this technology as it is not considered applicable at the study area.

3.3 HORIZONTAL WELL AIR SPARGING

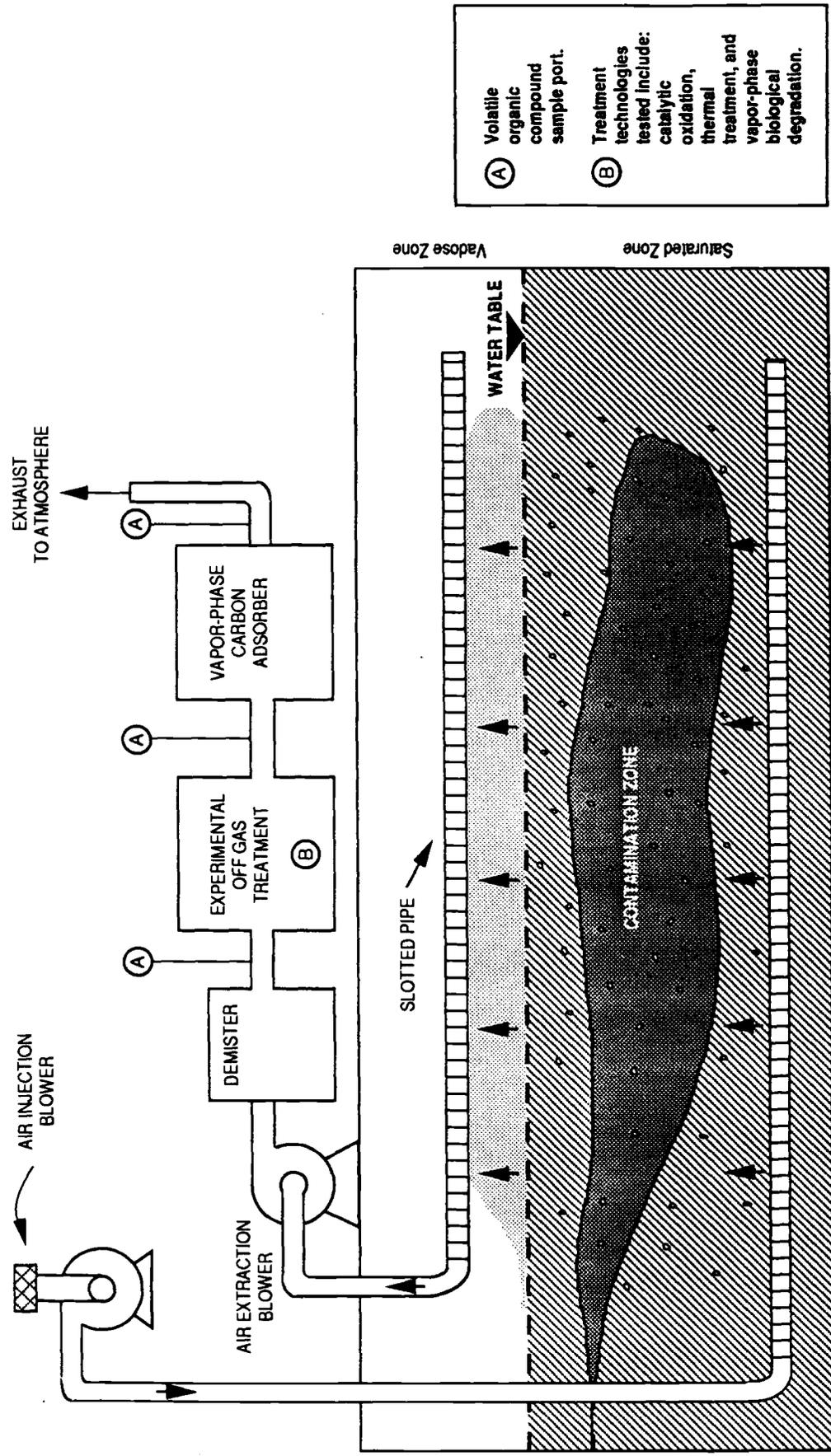
3.3.1 PROCESS DESCRIPTION

This technique combines the use of two technologies which have become well accepted separately: in-situ air sparging, which usually involves injection of air through a vertical well or wellpoint into an aquifer to strip volatiles from the groundwater and capillary fringe; and horizontal boring or well drilling, which is commonly used for enhanced petroleum recovery, non-intrusive utility installation, selective dewatering or groundwater recovery, and in-situ

volatilization of VOCs from soils. Air sparging with horizontal wells consists of injecting air via horizontally installed well screen(s) in the aquifer. The air sparging process itself only requires the installation of one horizontal sparging well below the water table. To prevent the uncontrolled release of contaminant vapors to the air or driving them into buildings and utility trenches, a second vapor extraction well is almost always installed in the vadose zone above the injection well.

The width of the area being treated is usually estimated as being equal to the depth of submergence of the injection well below the water table. This assumes that air bubbles will travel no more than half the distance horizontally that it rises vertically. The flow rate of vapor extraction should be at least equal to the rate of injection and perhaps two to three times as high to provide a factor of safety in preventing vapor migration.

With most contaminants and in most locations, offgas emission control is required prior to releasing the offgases to the atmosphere. In addition to testing air-sparging, the demonstration project was used to test the effectiveness of various offgas emission control technologies for chlorinated VOCs. Emission controls consisted of a primary and secondary control device in series. Primary offgas emission control was performed using catalytic oxidation, thermal destruction, and biological destruction, each being temporarily installed in the treatment train long enough to test the effectiveness and then replaced with the next experimental control device. Since the state did not recognize these methods as best available control technology (BACT), the offgas from these primary controls was also passed through a secondary or backup control system consisting of vapor-phase GAC to ensure removal of any breakthrough from the experimental emission control devices being tested. A typical process diagram of the air sparging system and emission control train is provided as Figure 3-3.



- (A) Volatile organic compound sample port.
- (B) Treatment technologies tested include: catalytic oxidation, thermal treatment, and vapor-phase biological degradation.

Figure 3-3
SCHEMATIC OF THE HORIZONTAL WELL AIR SPARGING PROCESS
AFP4 AND CAFB
FORT WORTH, TEXAS
 SOURCE: DOE, SAVANNAH RIVER, SOUTH CAROLINA; ESE.



Environmental
 Science &
 Engineering, Inc.

Specific advantages to the air sparging technology include the ability to remediate beneath buildings and other surface obstacles without disturbance, the removal of contaminants from groundwater and soils in situ (no treated water disposal requirement), and an increased aerobic biological activity in site soils and groundwater.

3.3.2 APPLICABILITY

This specific technology has been demonstrated at SRS to be appropriate for treating TCE in groundwater, and standard vertical-well air sparging has been well established as an effective remedy for VOCs in groundwater. TCE has a high vapor pressure and low solubility and thus volatilizes well from groundwater.

3.3.3 LIMITATIONS

This technology works best with a highly permeable granular aquifer and vadose zone with a high degree of homogeneity. Treatment is greatly hampered where injection rates are limited by permeability, vertical migration of air bubbles is prevented or hampered, and soil/aquifer heterogeneity produces preferential flow pathways for air and groundwater.

3.3.4 PROTOTYPE INSTALLATIONS

DOE's SRS has been the first full-scale test location for air sparging with horizontal wells, but the technique has since been licensed to several contractors and used at other government and commercial sites. No specifics of other sites have been provided in the literature reviewed or by personnel interviewed.

The SRS system consists of two horizontal wells, a lower-air sparging injection well and an upper vapor extraction well, installed using modified utility boring equipment. The lower well is approximately 300 ft long, is installed in the water table at a depth of approximately 140 feet below ground surface (ft-bgs), and is constructed of slotted polyethylene pipe. The upper well is approximately 200 ft

long, is installed in the vadose zone at a depth of approximately 50 ft-bgs, and is constructed of the same material as the lower well. The air injection rate was varied over three levels during the test: 65, 170, and 270 standard cubic feet per minute (scfm). Vapor extraction was performed at a constant 580 scfm for the duration.

3.3.5 RESULTS ACHIEVED

The combined SRS sparging/in-situ volatilization (ISV) process removed a total of 16,000 pounds (lb) of VOCs (TCE and PCE) from the soil and groundwater during a 140-day test. The rate of removal remained nearly constant for the duration of the test, ranging from approximately 175 pounds per day (lb/day) during the first four days, to 120 lb/day at the test midpoint, and decreasing slightly to 100 lb/day during the final 3 weeks (days 120 to 140). The test was deliberately not taken to completion to retain similar conditions for testing bio-sparging, as outlined in the following section. Confirmatory soil borings obtained after the completion of the test indicate a reduction of approximately 70 percent in the total mass of TCE in the soil and aquifer. No significant reduction in groundwater TCE concentrations occurred during the test. Since the test was not run to completion, it is not known what final groundwater and soil concentrations could have been achieved, or the length of time that would have been required to achieve applicable or relevant and appropriate requirements (ARARs) for soil and groundwater TCE concentrations. The cost incurred by DOE for this 139-day demonstration was \$416,286 in capital and \$62,620 in labor (Los Alamos National Laboratory, June 1992).

3.3.6 APPLICABILITY TO THE STUDY AREA

Air-sparging is proven to be effective on TCE, the contaminant of concern, but the stratigraphy at the AFP4 study area is far from ideal and differs radically from that at the SRS demonstration site. SRS soils are largely composed of sands and silts interspersed with clay fingers and lenses. The soils at AFP4 consist of a 3- to 5-ft thick surface layer of granular material (possibly fill),

underlain by a 15-ft-thick layer of "terrace alluvial material...composed of heterogeneous interbedded clay, silt, sand, and gravel" (hereafter referred to as terrace deposits) (Rust Geotech, 1993), and two limestone strata. The presence of perched groundwater (probably originating from leaking floor drains, sumps, and roof drains rather than naturally occurring) on the top of the terrace material indicates a low vertical permeability. The underlying upper zone aquifer is in limestone. Typically, limestone aquifers obtain the majority of their transmissivity from fractures and solution channels. If gases are injected into such an aquifer, gas pockets may form in the fractures and solution channels, driving groundwater away from the injection area rather than bubbling through the groundwater. Geological characterization in previous site reports refers to a 1- to 3-ft-thick weathered zone at the interface between the limestone and terrace deposits. It may be possible to prevent the aquifer from becoming air-bound by withdrawing air and vapor from this zone and by pulsing the injection cycles to minimize the size of air pockets. The rate of treatment will be limited by the rate of air injection, effective contact between the air and groundwater afforded by the flow paths in the solid matrix of the aquifer, and the ability of injected air to reach contaminated areas. The net result will most likely be to create large air pockets in the weathered interface between the limestone aquifer and overlying terrace deposits. Any contamination present in the terrace deposits will be largely untouched and continue to leach into the aquifer at nearly the same rate as currently exists. Flow can possibly be enhanced by pneumatic fracturing, but probably not sufficiently enough to create the desired uniform air flow.

3.3.6.1 Horizontal Well Air Sparging as Performed at SRS

This technology alone is neither a viable replacement for traditional groundwater pump-and-treat remediation, nor is it expected to significantly reduce the duration of remediation or the total number of gallons treated in achieving successful groundwater remediation at AFP4. This conclusion was reached for the following reasons:

1. Air sparging requires a large contact surface area between air water relative to the volume of water being treated. This is achieved by creating a large number of fine air bubbles within the volume of water being treated.
2. Because the aquifer at AFP4 is not granular, fine air bubbles cannot migrate freely upward and will quickly agglomerate into larger bubbles and air pockets within a few feet of the sparging point.
3. Groundwater in fissures and solution channels that receive some air contact will only be minimally treated because of the small air/water contact area, and water in channels, which bypass the sparged air, will not be treated at all.

Since air sparging is judged to be largely ineffective (groundwater contaminant concentrations would remain unacceptable and duration of treatment would be indefinite), a cost estimate was not developed for implementation of this alternative at the study area.

3.3.6.2 Modified Air Sparging Using Interception Trench(es)

In-situ air sparging may be a viable option for intercepting highly contaminated source flows to the alluvial aquifer between Building 181 and the vicinity of the "window area" when combined with the "permeable barrier" technology described in Section 3.1. An in-situ permeable barrier could be constructed across the path of the TCE plume by excavating a trench down to the underlying aquitard (approximately 30 ft) and backfilling it with coarse sand or pea gravel. The height of the permeable barrier would be equal to the maximum expected thickness of the aquifer plus a sufficient height of unsaturated material to allow for vapor removal (10 to 15 ft is expected to be adequate). Native material can be used for backfill in the remainder of the trench above the permeable barrier. If necessary, the trench would be lined with filter fabric to prevent migration of fines into the trench. A horizontal air sparging injection well would be installed along the bottom of the trench and a horizontal vapor extraction well installed in

the unsaturated upper level of the trench. A barrier length of approximately 1,000 to 1,500 ft would be required to span the alluvial groundwater plume near the window area. An injection rate of 1,000 cubic feet per minute (cfm) and extraction rate of 2,000 cfm are selected for purposes of this evaluation.

Since this technology will not remediate the downgradient portions of the alluvial aquifer or the plume in the Paluxy aquifer beneath the window area, conventional groundwater pump-and-treat remediation will still be required. Table 3-1 provides an estimate of remediation costs, using a 15-year air sparging operation and assuming a reduced duration of 15 years for air stripping pump-and-treat operations. This alternative costing assumes that sparging could remediate a large portion of the high-level TCE contamination in the source area alluvial aquifer before allowing mixing with the less contaminated downgradient alluvial and Paluxy aquifers, and that duration of pump-and-treat operations could thereby be halved (15 versus 30 years).

3.4 HORIZONTAL WELL BIO-SPARGING

3.4.1 PROCESS DESCRIPTION

Bio-sparging involves the introduction of nutrients along with air into a contaminated aquifer. Mechanically, it is nearly identical to the basic air sparging process described in Section 3.3. A process schematic diagram is provided in Figure 3-4. All of the elements necessary to implement air sparging are also required for bio-sparging. One notable exception is that bio-sparging can be effective at much lower air flow rates, since treatment is achieved by stimulating biological activity rather than volatilizing contaminants. The following paragraphs describe elements and considerations unique to bio-sparging.

Biological degradation of chlorinated hydrocarbons (PCE and TCE) and their intermediate breakdown products has been successfully demonstrated at the DOE SRS as well as other DOE/DOD sites (Appendix A.2). Addition of nutrients to

TABLE 3.1
COST ESTIMATE

Date Prepared: 06/22/94

Sheet 1 of 1

Project: AFP4

HORIZONTAL WELL AIR SPARGING ALTERNATIVE
WITH PERMEABLE IN-SITU BARRIER

224055

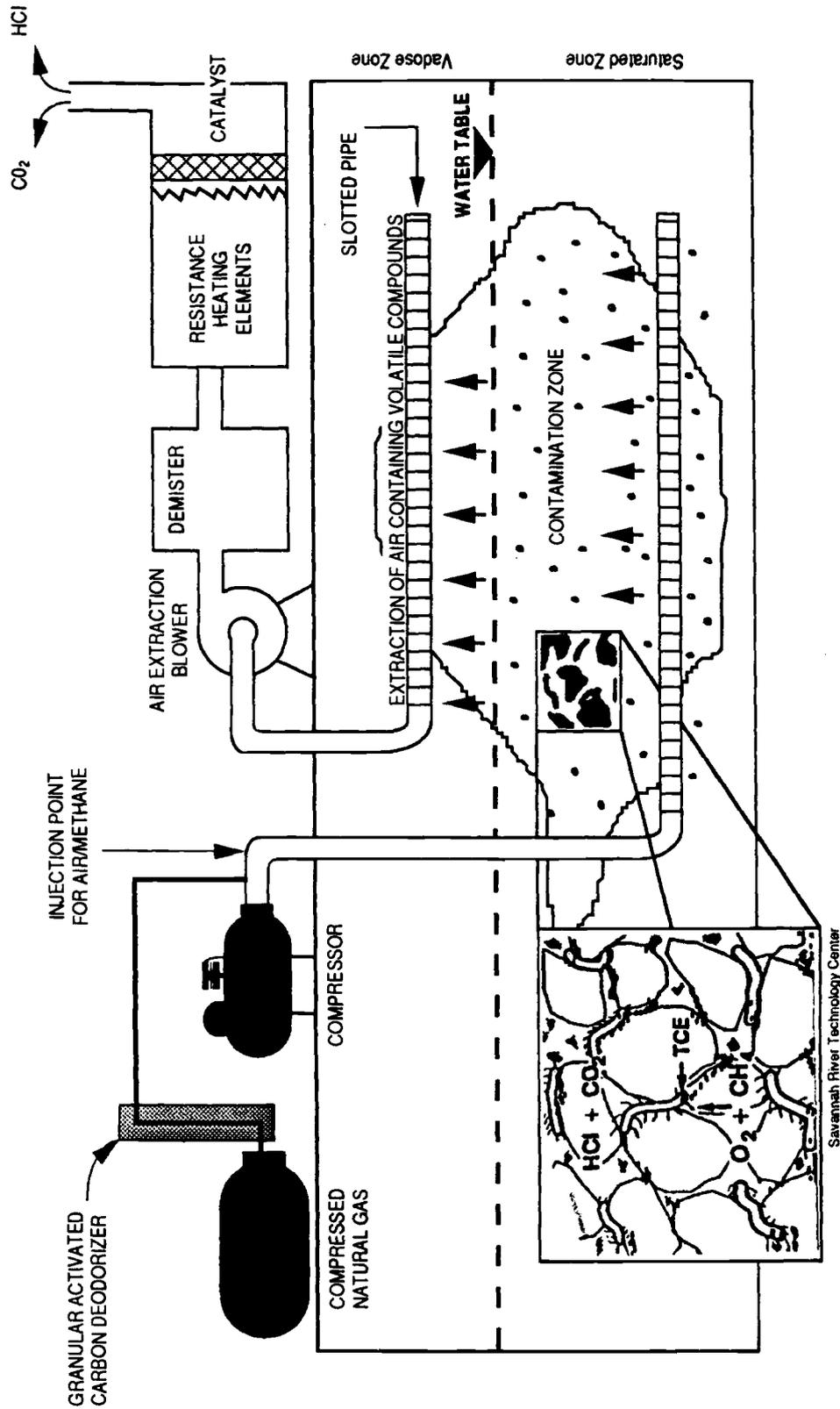
A/E: ESE (3932033G-0420-3130)

Drawing No. Estimator: GWW Checked By: Reviewed By:

Item No.	Description	Quantity		Labor & Equipment		Material		TOTAL COST
		No. Units	Unit Meas.	Per Unit	Total	Per Unit	Total	
PROJECT SUMMARY								
CAPITAL COSTS								
1.	Treatment System Pad							
A.	Concrete Pad (60'X80'X0.5') including compaction, labor and equipment	89	CY	\$9	\$833	\$60.50	\$5,378	\$6,211
B.	6" Curb	280	LF	\$2	\$818	\$3.10	\$868	\$1,484
C.	Steel reinforcement (#5 @ 12 each way)	5	TN	\$200	\$1,002	\$860	\$4,310	\$5,312
2.	Air Stripping Treatment System (500 gpm - same as Table 2.1)	1	LS					\$110,618
3.	Air Sparging Treatment System (1000cfm injection/2000 cfm extraction)							
A.	Sparging Well (35' deep, 1,250' long)	1250	LF	\$15	\$18,750	\$25.00	\$31,250	\$50,000
B.	Vacuum Recovery Well (15' deep, 1,250' long)	1250	LF	\$15	\$18,750	\$25.00	\$31,250	\$50,000
C.	Blowers, Piping, Other Eqpt.	1	LS	\$15,000	\$15,000	\$150,000	\$150,000	\$185,000
D.	Trench Excavation to 35'	6481	CY	\$20	\$129,630			\$129,630
E.	Sheeting and Shoring (left in place)	87500	SF	\$19	\$1,662,500	\$12.00	\$1,050,000	\$2,712,500
F.	Granular Filter Material	3241	CY	\$12	\$38,889	\$15.00	\$48,811	\$87,500
G.	Filter Fabric	4861	SY	\$0.20	\$972	\$0.25	\$1,215	\$2,188
ANNUAL GWTS OPERATION AND MAINTAINANCE COSTS								
1	Carbon Reactivation (4 Changeouts / year 10,000 lb capacity)	40000	lb			\$0.60		\$24,000
2	Power	317847	kwhr			\$0.06	\$19,071	\$19,071
3	Equipment replacement & Maintenance (5% of installed capital)	1	LS					\$168,176
4	Labor (2hrs per day)	730	hrs	\$45.00	\$32,850			\$32,850
5.	Monitoring (Sampling/Analysis by Method 8010)							
A.	Sample Cost (3 Samples + 1 Trip Blank Monthly)	48	ea	\$125.00	\$6,000			\$6,000
B.	Sample kit (1 kit Monthly)	12	ea	\$35.00	\$420			\$420
ANNUAL AIR SPARGING OPERATION AND MAINTAINANCE COSTS								
3.	Power	282800	kwhr			\$0.06	\$15,768	\$15,768
4.	Equipment replacement & Maintenance (5% of installed capital)	1	LS					\$8,250
5.	Additional Labor (1hr per day)	365	hrs	\$45.00	\$16,425			\$16,425
6.	Off-gas Carbon	15000	lb			\$0.60		\$9,000
7.	Additional Monitoring							
A.	Off-gas VOC and CO2	52	ea	\$100.00	\$5,200			\$5,200

Annual GWTS O&M	\$250,516
PV of GWTS O&M (15 yrs @ 5%)	\$2,600,274
Annual Air Sparging O&M	\$54,643
PV of Air Sparging O&M (15 yrs @ 5%)	\$236,576
Installed Capital	\$3,320,439
Contingency (25% of Capital)	\$830,110
Engineering (15% of Capital)	\$498,066
O&P (12% of Capital)	\$398,453
TOTAL COST	\$7,883,918

- Note: 1) Airstripping costs obtained from Table 2.1
 2) Concrete Slab cost estimated from Means 1994.
 3) Lab cost obtained from ESE lab
 4) No pretreatment, wellfield extraction, or piping costs included.
 5) Bio-sparging costs extrapolated from LANL 6/92 economic analysis
 Source: ESE, 1994



Environmental
Science &
Engineering, Inc.



Figure 3-4
SCHEMATIC OF THE HORIZONTAL WELL BIO-SPARGING PROCESS
AFP4 AND CAFB
FORT WORTH, TEXAS
SOURCE: DOE, SAVANNAH RIVER, SOUTH CAROLINA, ESE.

the soil/groundwater matrix results in the co-metabolism of the contaminants of concern as the primary nutrients are metabolized by indigenous or foreign microorganisms. Biodegradation of TCE in the presence of methane has been observed by researchers at the EPA, Stanford University, University of Tennessee, and Oak Ridge National Laboratory. Successful experiments include degradation in laboratory-scale aquifer columns, fluidized-bed bioreactors, and fixed-bed bioreactors.

Methanotrophs (methane-oxidizing bacteria) oxidize methane via a series of enzymes that are unique to these bacteria. The primary enzyme in this oxidation chain is methane monooxygenase (MMO). MMO is an extremely powerful oxidizer, which is able to oxidize contaminants such as PCE and TCE, usually considered refractory (Westinghouse SRC, September, 1991). Soluble MMO type I induces formation of TCE-epoxide from TCE. TCE-epoxide is extremely unstable and therefore spontaneously breaks down to simpler compounds. All of the daughter compounds are either unstable or small and easily metabolized, thus making the final and almost immediate end products of TCE-epoxide formation, carbon-dioxide and chloride salts. The methanotrophs obtain no benefit from the breakdown of TCE, which is merely a fortuitous side effect.

The rate of treatment or remediation is limited by the permeability of the soils. Low permeability will result in slow delivery of nutrients and slow remediation. Likewise, heterogeneity, with variable permeability from stratum to stratum, will result in preferential flow pathways and the majority of delivered nutrients will bypass some contaminated zones. Treatment will still be achieved at a slow rate in stagnant regions as nutrients reach them by diffusion.

Pilot-scale or full-scale in-situ biodegradation requires the presence of suitable methanotrophs; introduction of methane, oxygen, and micronutrients; and encouragement of liquid and gaseous flow into the contaminated zones of the aquifer and vadose zone.

The SRS Integrated Demonstration Project determined the presence of suitable microorganisms by microscopic plate counts of groundwater samples and by measuring the degradation rate of methane in the headspace gases of soil samples. SRS used horizontal wells to introduce oxygen and methane into the aquifer by air sparging. Methane concentrations never exceed 4 percent to prevent the possibility of fires or explosions [the lower explosive limit (LEL) for methane is 5.5 percent], Excess air, contaminant vapors, and products of decomposition are removed by a horizontal well vacuum extraction system in the vadose zone. Offgases are treated by catalytic oxidation at SRS to meet air quality permitting requirements; however, treatment can also be performed by vapor-phase carbon adsorption. Successful treatment is monitored by measuring methane, carbon dioxide, and TCE (and daughter product) vapor concentrations in the soil headspace gases, concentrations of TCE, methane, and chloride ion in groundwater, and residual TCE and daughter product concentrations in confirmatory soil samples taken after treatment. It is also possible to enhance and accelerate the process by addition of phosphorous and other micronutrients. Groundwater analyses monitor concentrations of other key enzymes whose presence indicates that the rate of treatment is being limited by micronutrients.

3.4.2 APPLICABILITY

This technology has been demonstrated at both SRS and Tinker AFB to be appropriate for treating TCE in groundwater and soils. As described previously, laboratory studies have proven the effectiveness of the biological co-metabolism of TCE and have accurately defined the mechanism (oxidation by MMO) by which treatment occurs.

3.4.3 LIMITATIONS

The mechanical limitations of this technology are similar to air sparging. Existing horizontal well boring equipment cannot install wells deeper than approximately 200 ft. Lighter duty equipment is limited to a depth of approximately 50 ft and a length of perhaps 300 ft, depending on soil plasticity

and the presence of boulders and cobbles. Well screen and casing materials must be able to withstand the stresses of drawing the pipe through the boring, as well as being flexible enough to follow the turn-radius of the boring without damage.

Low permeability and non-uniform permeability add complexity to the remediation and add greatly to the required time of remediation. The rate of treatment is limited by the rate at which nutrients diffuse into low-permeability zones of contamination or contaminant vapors diffuse out. Effective treatment is not as severely limited by these factors as is conventional air sparging since lower air flows can still yield acceptable rates of treatment. Duration and cost of remediation are difficult to estimate accurately with any in-situ treatment technology under the best of circumstances and especially in less-than-ideal stratigraphy.

The aquifer must be capable of growing and maintaining an adequate population of suitable methanotrophs. Toxicity, due to the nature of contaminants or naturally occurring compounds, can limit biological activity to ineffective levels. The use of indigenous organisms is preferable, since they have adapted to site conditions to some extent. If foreign organisms must be introduced, testing must be performed to verify adaptability.

3.4.4 PROTOTYPE INSTALLATIONS

Most development and testing of this technology to date has been laboratory-scale. Treatment has been demonstrated in soil columns at the EPA Ada, Oklahoma research laboratory and at Stanford University. A laboratory-scale bioreactor demonstration has been performed at ORNL and fluidized-bed bioreactors have been tested at SRS. Successful pilot-scale field applications include a pump-and-treat remediation of TCE-contaminated groundwater using a trickle-bed bioreactor at Tinker AFB in Oklahoma, in-situ methanotrophic biodegradation of TCE in a small area of a shallow aquifer at Moffett Naval Air

Station (NAS) in California, and the horizontal well bio-sparging demonstration at SRS.

3.4.5 RESULTS ACHIEVED

Because the bio-sparging test at SRS was part of an "integrated demonstration," the test was halted after 1 year rather than taken to completion. Approximately 22 percent or 8,000 lb of the original DNAPL contamination is estimated to remain in the Area M saturated and unsaturated zones. Destruction or removal of TCE was achieved, as indicated by the increase in free chloride ions and decrease in TCE concentrations, in some monitor wells. The overall effectiveness was not observed as groundwater concentrations were still several orders of magnitude above drinking water MCLs at the conclusion of the test. The destruction of TCE achieved should appreciably reduce the duration of a traditional pump-and-treat remediation, but there are insufficient data to evaluate how successful this technology would be if used as the sole remedy.

3.4.6 APPLICABILITY TO THE STUDY AREA

Bio-sparging is proven to be effective on TCE, the contaminant of concern, but, as with conventional air sparging, the stratigraphy at the study area is not conducive to providing air flow to all zones of contamination. Again, it may be possible to prevent the aquifer from becoming air-bound by withdrawing gases from this zone and by pulsing the injection cycles to minimize the size of air pockets. The intervals between injection would allow efficient utilization of the carbon source and micronutrients.

Bioremediation of the overlying terrace deposits (which may be a concentrated source contributing to the groundwater contamination) may be possible by injection of air and gaseous nutrients through horizontal wells. Establishment of flow patterns and adequate recovery of injected gases must be determined by tracer gas (helium or other) testing. If permeabilities are not adequate, flow can possibly be enhanced by pneumatic fracturing. Unlike conventional air sparging,

this technology does not depend on such intense air flow density in the contaminated zones, since treatment can occur in relatively stagnant areas as gases diffuse in and bacteria follow.

This technology is probably not a viable replacement for traditional groundwater pump-and-treat remediation, but may be significantly effective in reducing the duration of remediation and the total number of gallons treated over the life of the project.

Table 3-2 provides an estimate of remediation costs, using a 5-year bio-sparging operation and assuming a reduced duration of 15 years for air stripping pump-and-treat operations. This alternative costing assumes that a 1,500-ft-long horizontal bio-sparging well installed near Building 181 could remediate a large portion of the DNAPL contamination in the source area alluvial aquifer and terrace deposits, and that the duration of pump-and-treat operations could be halved (15 versus 30 years).

3.5 TITANIUM DIOXIDE PHOTOCATALYTIC OXIDATION

3.5.1 PROCESS DESCRIPTION

The use of UV radiation in conjunction with a photocatalyst to oxidize TCE has been the subject of numerous investigations (Ahmed, 1984; Matthews, 1986; and Magrini, 1990). Ahmed and Ollis (1984) were among the first groups to use the UV radiation driven photocatalytic oxidation reactions of TCE on a laboratory scale. This technology is applicable for the remediation of contaminated air or water streams. Matthews (1986) and Magrini (1990) have used titanium dioxide (TiO_2) catalyst to photocatalytically destroy TCE in water. Photocatalytic reactors of different configurations have also been investigated (Bedford et al., 1991).

The basic component of the TiO_2 photocatalytic oxidation system is a photocatalytic reactor cell. The cell is comprised of an outer stainless steel jacket

TABLE 3.2 COST ESTIMATE		Date Prepared: 06/20/94 Sheet 1 of 1						
Project: AFP4		HORIZONTAL WELL BIO-SPARGING ALTERNATIVE						
A/E: ESE (3932033G-0420-3130)								
Drawing No.		Estimator: GWW		Checked By:		Reviewed By:		
Item No.	Description	Quantity		Labor & Equipment		Material		TOTAL COST
		No. Units	Unit Meas.	Per Unit	Total	Per Unit	Total	
PROJECT SUMMARY								
CAPITAL COSTS								
1.	Treatment System Pad							
A.	Concrete Pad (60'X80'X0.5') including compaction, labor and equipment	89	CY	\$9	\$833	\$60.50	\$5,378	\$6,211
B.	6" Curb	280	LF	\$2	\$616	\$3.10	\$868	\$1,484
C.	Steel reinforcement (#5 @ 12 each way)	5	TN	\$200	\$1,002	\$860	\$4,310	\$5,312
2.	Air Stripping Treatment System (500 gpm - same as Table 2.1)	1	LS					\$110,616
3.	Bio-Sparging Treatment System (300cfm injection/400 cfm extraction)							
A.	Sparging Well (75' deep, 500' long)	500	LF	\$200	\$100,000	\$100.00	\$50,000	\$150,000
B.	Vacuum Recovery Well (20' deep, 400' long)	400	LF	\$150	\$60,000	\$100.00	\$40,000	\$100,000
C.	Blowers, Piping, Other Eqpt.	1	LS	\$10,000	\$10,000	\$100,000	\$100,000	\$110,000
D.	Nutrient Injection Eqpt	1	LS	\$3,000	\$3,000	\$30,000	\$30,000	\$33,000
E.	Bio-Assay and Bench Test	1	LS					\$25,000
ANNUAL GWTS OPERATION AND MAINTAINANCE COSTS								
1.	Carbon Reactivation (4 Changeouts / year 10,000 lb capacity)	40000	lb			\$0.60		\$24,000
2.	Power	317847	kw/hr			\$0.06	\$19,071	\$19,071
3.	Equipment replacement & Maintenance (5% of installed capital)	1	LS					\$29,235
4.	Labor (2hrs per day)	730	hrs	\$45.00	\$32,850			\$32,850
5.	Monitoring (Sampling/Analysis by Method 8010)							
A.	Sample Cost (3 Samples + 1 Trip Blank Monthly)	48	ea	\$125.00	\$6,000			\$6,000
B.	Sample kit (1 kit Monthly)	12	ea	\$35.00	\$420			\$420
ANNUAL BIO-SPARGING OPERATION AND MAINTAINANCE COSTS								
1.	Methane (de-odorized compressed natural gas)	1028348	Therm			\$0.10	\$102,835	\$102,835
2.	Chemical Additives (phosphorous, ammonia @ 30% methane cost)	1	LS					\$30,850
3.	Power	131400	kw/hr			\$0.06	\$7,864	\$7,864
4.	Equipment replacement & Maintenance (5% of installed capital)	1	LS					\$20,900
5.	Additional Labor (1hr per day)	365	hrs	\$45.00	\$16,425			\$16,425
6.	Off-gas Carbon	15000	lb			\$0.60		\$9,000
7.	Monitoring							
A.	Off-gas VOC and CO2	52	ea	\$100.00	\$5,200			\$5,200
B.	Groundwater Bioassay (5 wells/quarter)	20	ea	\$125.00	\$2,500			\$2,500
C.	Groundwater Chloride (5 wells/quarter)	20	ea	\$25.00	\$500			\$500
								\$111,576
Annual GWTS O&M								\$111,576
PV of GWTS O&M (15 yrs @ 5%)								\$1,158,116
								\$196,094
Annual Bio-sparge O&M								\$196,094
PV of Bio-sparge O&M (5 yrs @ 5%)								\$848,985
								\$541,622
Installed Capital								\$541,622
								\$135,406
Contingency (25% of Capital)								\$135,406
								\$81,243
Engineering (15% of Capital)								\$81,243
								\$64,995
O&P (12% of Capital)								\$64,995
TOTAL COST								\$2,830,367

Note: 1) Airstripping costs obtained from Table 2.1
 2) Concrete Slab cost estimated from Means 1994.
 3) Lab cost obtained from ESE lab
 4) No pretreatment, wellfield extraction, or piping costs included.
 5) Bio-sparging costs extrapolated from LANL 6/92 economic analysis
 Source: ESE, 1994

which contains the process stream (groundwater), and an internal jacket consisting of a UV lamp.

The cells can be linked in a serial mode and/or parallel mode depending on the concentration of the contaminants, the required throughput, and the amount of organic destruction desired.

The UV lamp emits low intensity light [normally 254 nanometers (nm)] and is mounted coaxially within the jacket. A multilayered sleeve of special fiberglass mesh bonded with TiO_2 lies around the lamp to form the catalytic matrix. The TiO_2 catalyst is activated by the light to produce hydroxyl (OH^\cdot) radicals. Depending on the contaminant concentration in the groundwater, hydrogen peroxide (H_2O_2) is also used in conjunction with TiO_2 to produce OH^\cdot radicals. The TCE-contaminated groundwater flows into the reactor and passes through the catalyst matrix where TCE is oxidized and reduced into CO_2 , water, and chloride ions. Figure 3-5 presents a schematic of the process. As shown in the figure, the treatment system consists of a photocatalytic reactor consisting of photocatalytic cell(s), UV lamps, an equalization tank, a discharge holding tank, and transfer pumps. It also shows that TiO_2 is used to generate the OH^\cdot radicals for the photocatalytic oxidation process.

3.5.2 APPLICABILITY

The TiO_2 photocatalytic treatment technology is applicable for the remediation of air or water contaminated with organic compounds. The technology has the following advantages:

1. Functions over a broad range of temperatures, pressures, and pH;
2. Not adversely affected by humidity;
3. Able to destroy highly resistive organics (DNT, CCl_4);
4. Does not suffer from organic fouling or the oxidation of iron; and
5. Applicable to both vapor and liquid-phase contaminated streams.

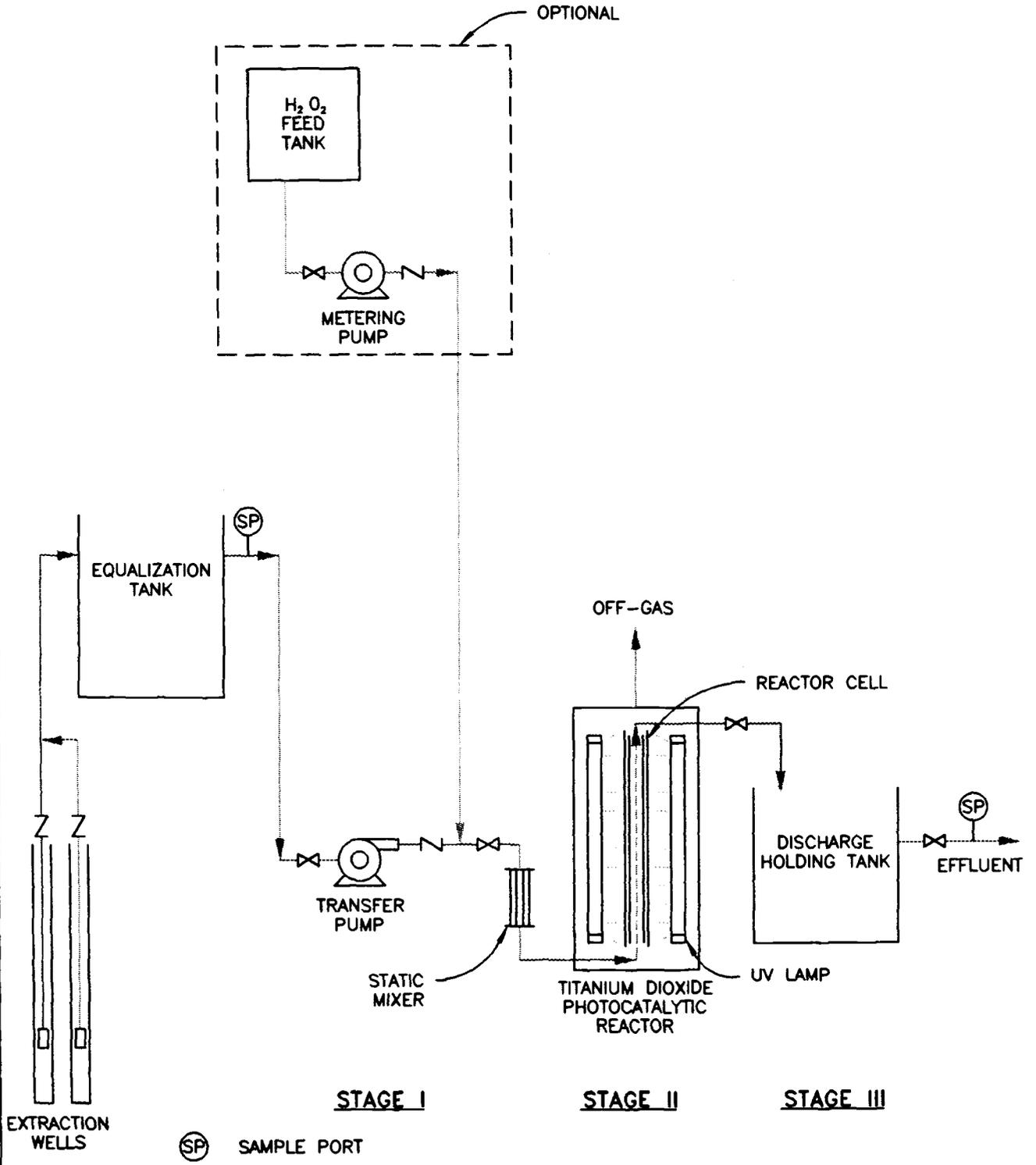


Figure 3-5
 SCHEMATIC OF TiO₂ PHOTOCATALYTIC
 OXIDATION PROCESS
 AFP4 AND CAFB, FORT WORTH, TEXAS
 SOURCE: ESE, 1994.



**Environmental
 Science &
 Engineering, Inc.**

Jun 10, 1994 - 08:35:11

3.5.3 LIMITATIONS

The treatment systems are modular in construction and can treat air or water streams up to 1,000 scfm and 100 gpm, respectively. A bench-scale treatability study would be required before a pilot or full-scale implementation of the technology.

3.5.4 PROTOTYPE INSTALLATIONS

DOE initiated a program to accelerate the development and testing of the photocatalytic oxidation technology for hazardous wastes. This program is designed to propel the technology from the laboratory to actual waste sites (Gupta, 1991).

The SITE program accepted this technology for pilot testing. In October 1992, this innovative technology was evaluated for the remediation of groundwater contaminated with TCE at SRS in South Carolina.

During the summer of 1992, the technology was evaluated at Tyndall Air Force Base (TYAFB) for the remediation of groundwater contaminated with benzene, toluene, ethylbenzene, and xylenes (BTEX) compounds. Solar radiation was used as a source of energy for UV light.

3.5.5 RESULTS ACHIEVED

The photocatalytic oxidation technology was evaluated at SRS for the remediation of TCE-contaminated groundwater. The offgas generated by vacuum extraction technique was treated by this technology. Field tests were conducted with different influent concentrations of TCE [138 to 193 parts per million by volume (ppmv)] and air flow rates (25 to 75 scfm). The results were inconsistent in achieving TCE destruction efficiencies (60 to 98 percent) (Matrix Photocatalytic, Inc., 1993). It was recommended that the path length of the reactor be increased to achieve higher destruction efficiencies in a consistent manner. During the site visit by an ESE engineer in March 1994, no offgas

treatment technologies, including photocatalytic oxidation technology, were in use at SRS.

During the field test of this technology at TYAFB, it was observed that lowering the pH did not have a significant impact on the reaction rate. Lowering the TiO_2 loading rate from 0.1 to 0.05 percent reduced the reaction rate by about 20 percent. The addition of H_2O_2 to the groundwater has a significant impact on the rate of destruction of BTEX. The exact mechanism for rate enhancement was not determined. The field tests showed destruction efficiencies of BTEX between 50 and 75 percent.

3.5.6 APPLICABILITY TO THE STUDY AREA

The results of the field study at SRS are not encouraging. Three field trials were conducted at this site, but only one field trial resulted in a higher TCE destruction efficiency (98 percent). No further studies of this technology on TCE remediation have been reported.

This technology is in the developmental stage for TCE application and further development of the technology is necessary for a full-scale application. Based on the status of the technology development, this technology is not considered applicable for the remediation of groundwater at the study area.

A cost estimate for the remediation of TCE-contaminated groundwater is presented in Table 3-3. This technology is not considered applicable at the study area; however, a cost estimate was developed for comparison with a similar technology (UV/ H_2O_2). The assumptions made when developing the cost estimate were as follows:

1. Groundwater flow rate of 500 gpm,
2. Influent TCE concentration of 2.7 mg/L,
3. Targeted effluent concentration of 3.0 $\mu\text{g/L}$,
4. No groundwater pretreatment is required, and

Table 3.3

COST ESTIMATE

Project: AFP4

TiO2 WITH UV RADIATION

224067

A/E: ESE (3932033G-0420-3130)

Q = 500gpm, Influent Conc. = 2.7 mg/l, Effluent Conc = 3.0 µg/l

Drawing No.

Estimator: JRP

Checked By:

Reviewed By:

Item No.	Description	Quantity		Labor & Equipment		Material		TOTAL COST	
		No. Units	Unit Meas.	Per Unit	Total	Per Unit	Total		
I CAPITAL COSTS									
1.	Treatment system Pad (60'X80'X0.5') including concrete, compaction, labor and equipment	89	CY	\$9.37	\$833	\$61	\$5,378	\$6,211	
a.	6" Curb	280	LF	\$2.20	\$616.00	\$3.10	\$888.00	\$1,484	
2.	Equalization Tank (15,000 gal Belco, 12ft d X 18ft Straight Sidewall, Vertical dome top, flat bottom fiberglass. Includes 6in Gussetted flanges, gooseneck vent, 18 in side manway, hold down lugs, lifting lugs.)	1	ea	\$10,027	\$10,027			\$10,027	
3.	TiO2 Photocatalytic System w/ 60 standard Modules of 72 Photocells (12 wafers of 6 cells) each 8 gpm/wafer, \$40,000 / module	1	LS	\$2,400,000	\$2,400,000			\$2,400,000	
II ANNUAL OPERATION AND MAINTANCE COSTS									
1.	Power (5.5 kw / module), 60 modules	2890800	kwhr			\$0.06	\$173,448	\$173,448	
2.	Equipment Maintenance and Replacement								
A.	Light Source / 2 yrs \$50.00 / unit, 4320 units)	2160	ea			\$50.00	\$108,000	\$108,000	
B.	Replacment Mesh (TiO2), each cell	4320	ea			\$50.00	\$216,000	\$216,000	
3.	Hydrogen Peroxide (50% Soln)	9300	lb			0.65	\$6,045	\$6,045	
a.	Hydrogen Peroxide Storage and Handling (10% of Cost)	1	LS				\$605	\$605	
III Monitoring (Sample/Analysis by EPA Method 8010)									
A.	Sample Cost (2 Samples + 1 Trip Blank Monthly)	36	ea	\$125.00	\$4,500			\$4,500	
B.	Sample kit (1 kit Monthly)	12	ea	\$35.00	\$420			\$420	
								Annual O&M	\$609,018
								PV of O&M (30 yrs @ 5%)	\$7,824,847
								Installed Capital	\$2,417,722
								Contingency (25% of Capital)	\$604,430
								Engineering (15% of Capital)	\$362,658
								O&P (12% of Capital)	\$290,127
TOTAL COST								\$11,499,784	

Note: 1) Tank, TiO2 System, UV Peroxide cost obtained from vendor.
 2) Lab cost obtained from ESE lab
 3) Concrete Slab cost estimated from Means 1994.
 4) No Pretreatment, wellfield extraction, or piping costs included.
 Source: ESE, 1994

5. O&M required for 30 years.

As shown in Table 3-3, the TiO₂ photocatalytic system is the major component of the capital cost. TiO₂ cell replacement and the power consumption are the major portions of the O&M costs. The approximate capital and annual O&M costs are \$2,400,000 and \$500,000 respectively.

3.6 TWO-STAGE METHANOTROPHIC BIODEGRADATION

3.6.1 PROCESS DESCRIPTION

The objective of the methanotrophic bioremediation is to remove organic constituents from the waste stream via methanotrophic microbial degradation, a two-stage process. In Stage I, a methanotrophic microbial population (culture medium) is developed in a culture vessel by injecting methane, nutrients, and air. Methanotrophs (methane-oxidizing bacteria) oxidize methane via a series of enzymes that are unique to these bacteria. The primary enzyme in this oxidation chain is MMO, a powerful oxidizer. Stage I reaction must develop a dense population of methanotrophs and an excess quantity of MMO. In Stage II, the culture medium developed in the Stage I process is used to treat groundwater contaminated with TCE. The solution containing MMO and methanotrophic bacteria developed in the Stage I culture vessel is pumped to a plug flow reactor where it is mixed with the TCE-contaminated groundwater. As a result of MMO-induced oxidation in the reactor, the TCE in wastewater is decomposed into harmless end products (CO₂ and HCl). The treated effluent from the plug flow reactor flows into a holding tank for monitoring prior to disposal and for possible recirculation, if discharge limits are not achieved. Figure 3.6 presents a schematic of the process. As shown in the figure, the major components of the treatment system include a culture vessel, a plug flow reactor, holding tanks for the influent and effluent streams, nutrients and transfer pumps.

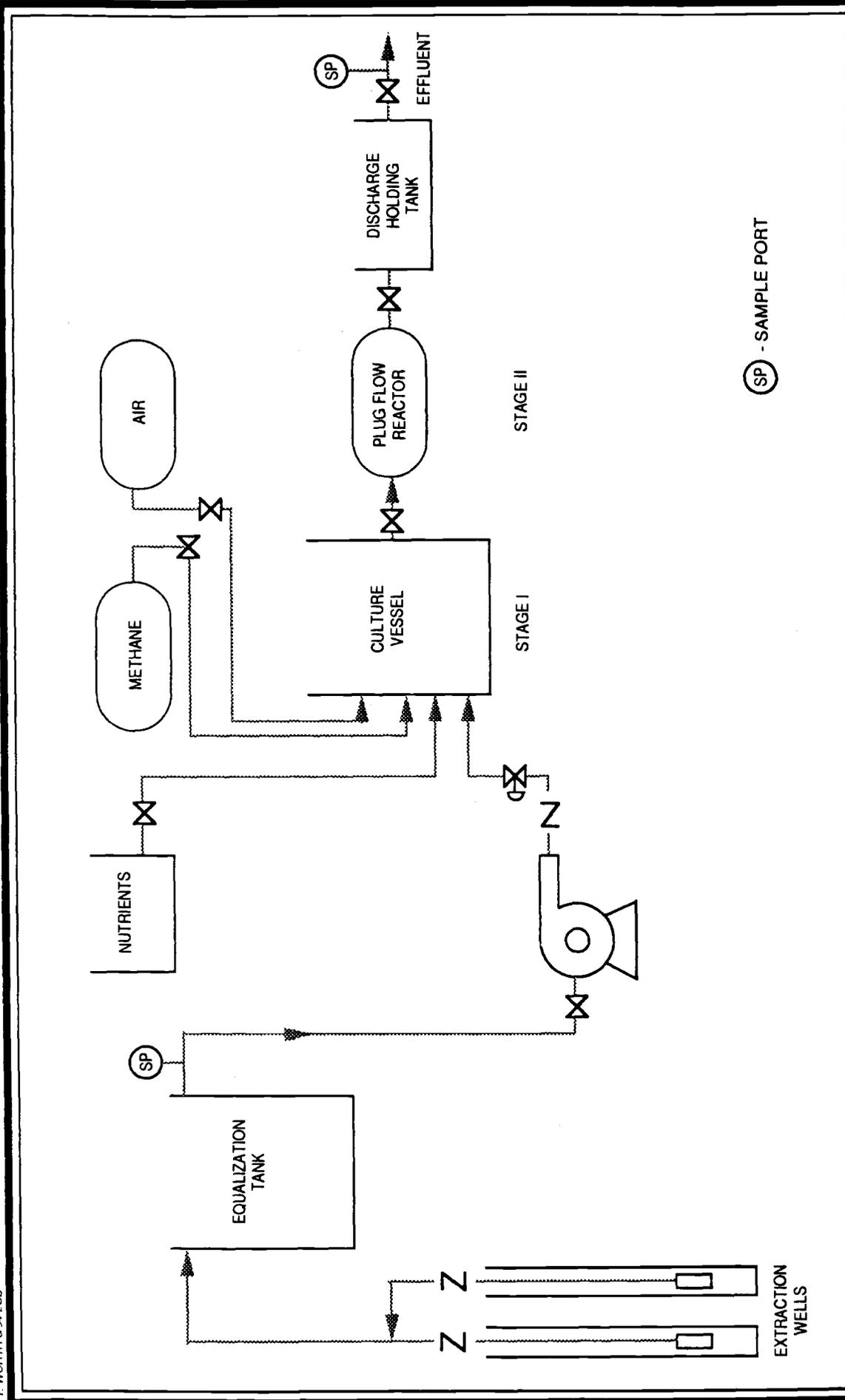


Figure 3-6
SCHEMATIC OF THE TWO-STAGE METHANOTROPHIC BIODEGRADATION PROCESS
AFP4 AND CAFB
FORT WORTH, TEXAS
 SOURCE: BIOTROL, INC., ESE.



Environmental
 Science &
 Engineering, Inc.

3.6.2 APPLICABILITY

The methanotrophic biodegradation technology is applicable for the remediation of groundwater contaminated with halogenated aliphatic hydrocarbons including TCE, dichloroethylene isomers, vinyl chloride, dichloroethane isomers, chloroform, and dichloromethane.

3.6.3 LIMITATIONS

The application of this technology is limited to the destruction of halogenated aliphatic hydrocarbons in water. The growth and stability of the methanotrophs developed within the culture vessel in Stage I (Section 3.6.1 for details) are critical for the biodegradation of the contaminants.

3.6.4 PROTOTYPE INSTALLATIONS

In 1990, the methanotrophic biodegradation technology was accepted into the SITE Emerging Technology Program. In 1993, a prototype system for methanotrophic biodegradation was installed and operated by BioTrol, Inc., Eden Prairie, Minnesota, at their testing facility.

3.6.5 RESULTS ACHIEVED

For the prototype test, the average influent and effluent concentrations of TCE were 560 and 60 $\mu\text{g/L}$, respectively. The prototype test was successful in degrading TCE by 89 percent. The reaction kinetics were consistent with first-order biodegradation kinetics; however, day-to-day treatment efficiency changed considerably even though the cell growth rate remained constant. Also, there was variability in the degree of TCE degradation and difficulty in maintaining the activity of the microbial culture in the Stage I process.

3.6.6 APPLICABILITY TO THE STUDY AREA

The pilot test was unsuccessful in achieving the stable culture medium required to degrade TCE in water. Further testing is required to achieve a stable culture medium for long-term applications of this technology for TCE-contaminated

groundwater. Therefore, methanotrophic biodegradation technology is not considered applicable at the study area.

A cost estimate was not prepared for this technology as it is not considered applicable at the study area.

3.7 HIGH-ENERGY ELECTRON BEAM IRRADIATION

3.7.1 PROCESS DESCRIPTION

High-energy electron beam irradiation (HEBI) is an innovative treatment process for the destruction of organic chemicals in groundwater. The process uses a beam of accelerated electrons to separate water molecules, forming several reactive chemical species that rapidly decompose organic compounds to innocuous byproducts. Irradiation of aqueous solutions with high-energy electrons results in the formation of the aqueous electron, hydrogen radical, and the hydroxyl radical. These reactive transient species initiate chemical reactions capable of destroying organic compounds in aqueous solution.

In this process, water containing organic compounds is directed over a weir, where it falls in a thin sheet (approximately 4 mm thick). A 1.5-million volt insulated core transformer (ICT) electron accelerator generates electrons and accelerates them to approximately 97 percent of the speed of light. The accelerated electrons are propelled in a concentrated beam down a 100-inch high-vacuum tube toward a scanner that scans the beam to a rectangular shape and directs it toward the aqueous solution that is flowing over the weir. The electrons then pass through a thin titanium window (1/1,000 of an inch). The electrons penetrate the waste stream and destroy the organic contaminants. The extent to which organic compounds are broken down is different for each compound. However, with enough energy, all organic compounds decompose into CO₂, water, and salts. Figure 3-7 presents a schematic of the process. As shown in this figure, the major components of the treatment system include an electron accelerator, an influent spreader, and an effluent sampling area.

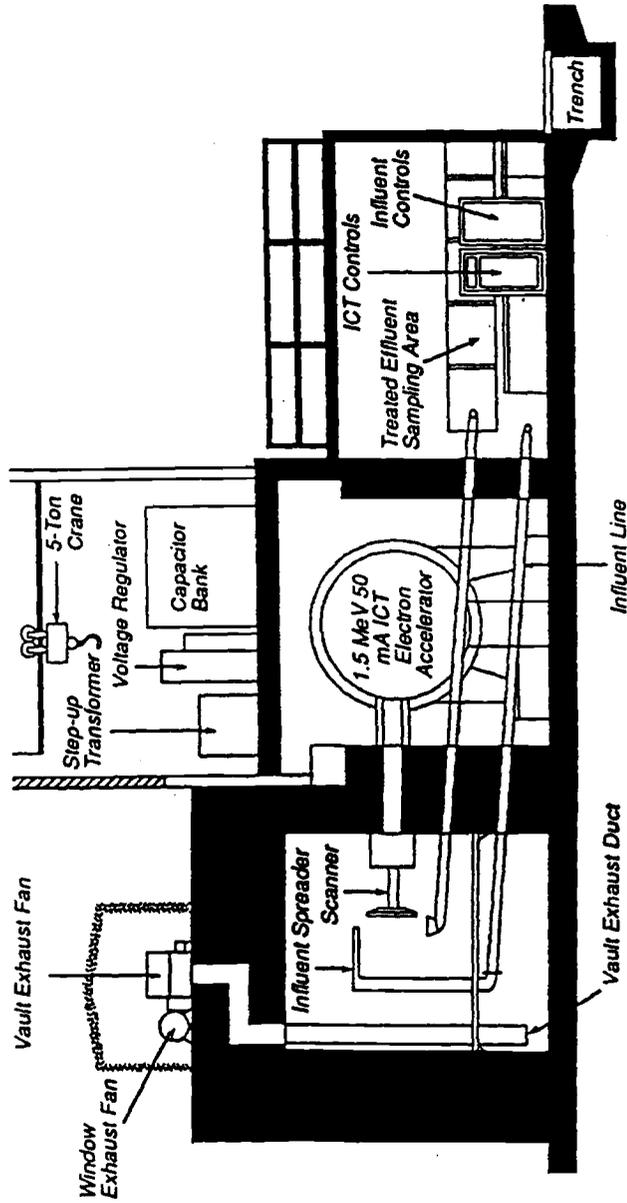


Figure 3-7
SCHEMATIC OF THE HIGH ENERGY ELECTRON BEAM
IRRADIATION PROCESS
AFP4 AND CAFB, FORT WORTH, TEXAS
 SOURCE: EBRF, UNIVERSITY OF MIAMI.



Environmental
 Science &
 Engineering, Inc.

The process is a continuous flow system but can be operated in a batch mode. The dosage of electrons is expressed in kilorads (krad) and typically fluctuates between 645 and 800 krad at full power in most applications. The process has the following advantages:

1. Nonselective in the destruction of organic chemicals,
2. Reaction time is less than a second,
3. pH and temperature independent, and
4. No organic sludge or air emissions.

3.7.2 APPLICABILITY

Studies using HEBI have demonstrated that the process is efficient for the destruction of several classes of hazardous organic compounds including chloroform, bromodichloromethane, dibromochloromethane, bromoform, CCl₄, TCE, tetrachloroethylene, trans-1,2-dichloroethylene, cis-1,2-dichloroethylene, dichloroethane, methylene chloride, benzene, toluene, ethylbenzene, chlorobenzene, xylenes, dieldrin, and phenol.

3.7.3 LIMITATIONS

Although TCE destruction efficiencies greater than 99 percent were observed, stable oxidized polar organic compounds were formed as a result of the irradiation of TCE. These compounds consist of formic acid, formaldehyde, and acetaldehyde. The concentrations of these compounds in the effluent varied depending on the radiation dosage (krads).

3.7.4 PROTOTYPE INSTALLATIONS

A prototype facility was installed and operated at the Electron Beam Research Facility (EBRF), Miami-Dade Water and Sewer Authority Department, Virginia Key Wastewater Treatment Plant, Miami, Florida. It was funded by the National Science Foundation (NSF), EPA, and DOE.

Studies were conducted at EBRF for the destruction of TCE in water. Greater than 99 percent destruction efficiencies were achieved at a 120-gpm flow rate (Kurucz, 1992; Cooper, 1993).

3.7.5 RESULTS ACHIEVED

Prototype experiments were conducted at EBRF and wastewater containing several organic compounds was tested using the HEBI technology. The organic compounds tested include phenol (SITE, 1993), TCE (SITE, 1992; Cooper, 1993), tetrachloroethene (Cooper, 1993), benzene, and toluene (Nickelsen, 1992). Greater than 99 percent removal efficiencies were reported for TCE (Kurucz, 1992).

3.7.6 APPLICABILITY TO THE STUDY AREA

Although prototype tests were successful in destroying TCE in water, reaction byproducts were formed as a result of irradiation of water. The technology requires further evaluation before full-scale implementation. This technology is not, therefore, considered applicable for the remediation of groundwater at the study area.

A cost estimate was not prepared for this technology as it is not considered applicable at the study area.

3.8 ULTRASONIC DETOXIFICATION

3.8.1 PROCESS DESCRIPTION

The ultrasonic detoxification process is an innovative treatment process for the destruction of chlorinated organic compounds in water. The process involves the use of intensive ultrasonic-energy waves (high-frequency sound) to transform the chlorinated organic compounds in water into nonhazardous end products.

The ultrasonic-energy waves are produced in an ultrasonic irradiation chamber. The chamber is designed to provide a sufficient residence time for water to

achieve the desired destruction rate for the contaminants. The ultrasonic waves generated from the chamber produce an alternating adiabatic compression and rarefaction (expansion) of the groundwater being irradiated. Compression cycles exert a positive pressure on the water, pushing the molecules together, and the expansion cycles exert a negative pressure, pulling the molecules away from one another. During the expansion cycle, a sound wave of sufficient intensity generates cavities within the molecule, which grow gradually with the expansion and compression cycles. When a critical size is attained, the compression portion of the wave violently collapses the cavities, creating extremely high local temperatures [up to 5,000 degrees Kelvin (K)] and high pressures (up to 500 atmospheres). Under such conditions, water decomposes into extremely reactive OH^\cdot radicals and hydrogen atom (H^\cdot). During the subsequent cooling phase, OH^\cdot and H^\cdot combine to form H_2O_2 and H_2 . The organic compounds present in water are rapidly destroyed in this environment. Figure 3-8 presents a schematic of the process. As shown in this figure, the major components of the treatment system include an ultrasonic reactor, an equalization tank, a holding tank for the effluent, an oxidant storage tank, and transfer pumps.

3.8.2 APPLICABILITY

The ultrasonic detoxification process is applicable for the remediation of groundwater contaminated with chlorinated organic compounds. This technology was evaluated on a laboratory scale for the remediation of water contaminated with CCl_4 . Destruction efficiencies greater than 99 percent were observed during the study with approximately 8 minutes of irradiation (Wu, 1992).

3.8.3 LIMITATIONS

Although successful results were achieved on the bench-scale level with CCl_4 , no data are available on TCE destruction. Also, no other contaminants were tested on a large scale using this technology. Therefore, the engineering data required

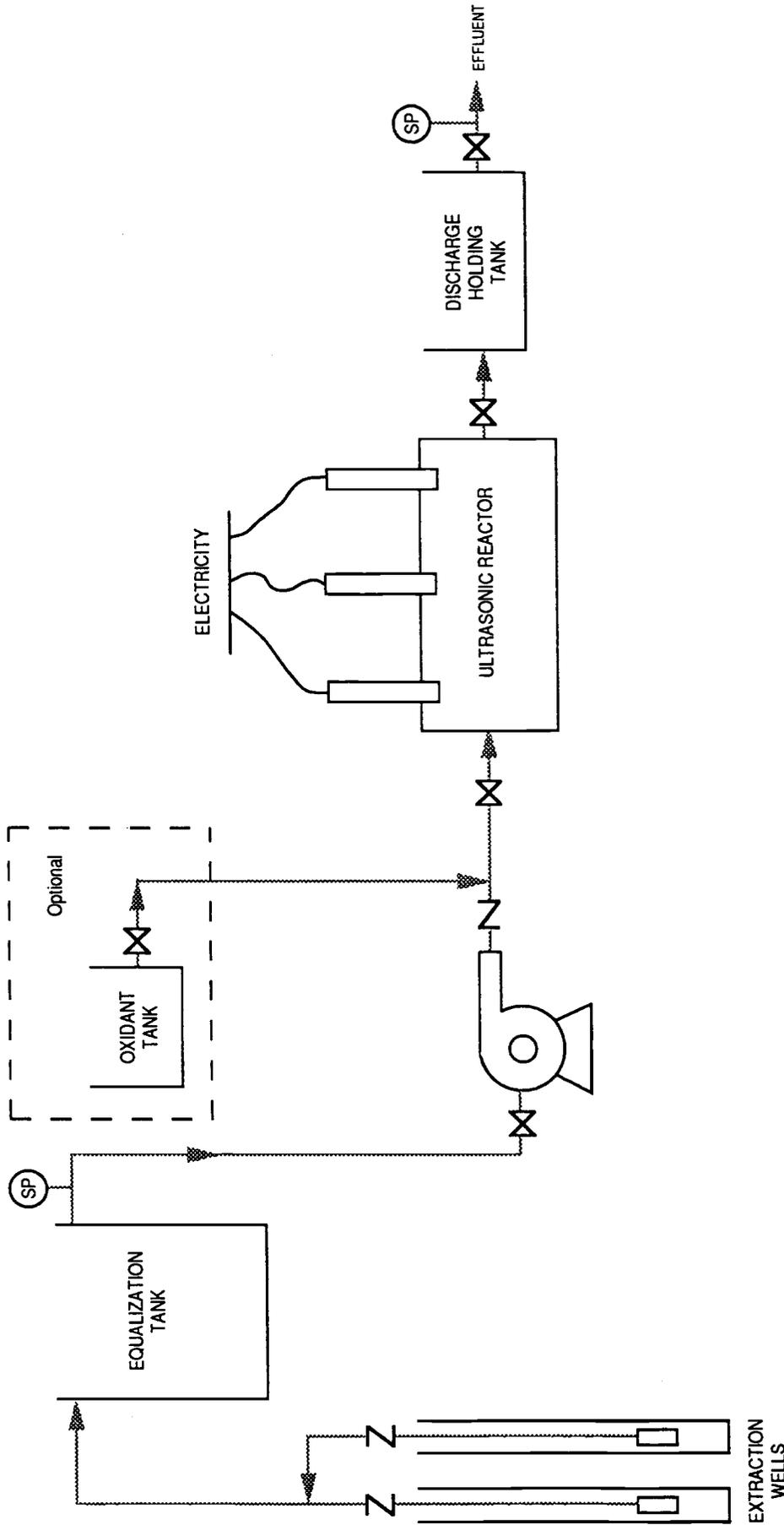


Figure 3-8
SCHEMATIC OF THE ULTRASONIC-DETOXIFICATION PROCESS
AFP4 AND CAFB, FORT WORTH, TEXAS

SOURCE: EBRF, UNIVERSITY OF MIAMI.



for the design of a commercial-scale continuous flow facility for TCE destruction are not available.

3.8.4 PROTOTYPE INSTALLATIONS

The bench-scale work on the ultrasonic detoxification process was conducted by the Argonne National Laboratory, Illinois, and was sponsored by DOE (Peters, 1991). An in-house pilot-scale study was conducted on CCl_4 . No prototype installations for application of this technology for the remediation of water contaminated with TCE were identified.

3.8.5 RESULTS ACHIEVED

The ultrasonic detoxification process was evaluated for the remediation of water contaminated with CCl_4 and was deemed successful. Destruction efficiencies greater than 99 percent were obtained with approximately 8 minutes of irradiation. The following results were obtained from the study:

1. At low concentrations of CCl_4 , the rate of destruction is first order;
2. The rate of destruction is dependent on the ultrasonic energy;
3. Temperature and pH have little effect on the process; and
4. Addition of small amounts of H_2O_2 has no effect.

3.8.6 APPLICABILITY TO THE STUDY AREA

This technology was not evaluated with TCE-contaminated water; therefore, the engineering data for the design of a commercial-scale facility are not available. This technology appears promising for CCl_4 -contaminated groundwater; however, it is not considered to be applicable for the remediation of TCE-contaminated groundwater at the Study Area because the technology is in infancy and its applicability to the destruction of TCE in groundwater has not yet been developed.

A cost estimate was not prepared for this technology as it is not considered applicable at the study area.

3.9 PARTITIONING TRACER TESTING

3.9.1 PROCESS DESCRIPTION

NAPL-Partitioning Tracer Testing (NPTT), used for the detection of DNAPL, is an emerging technology. The objective of the technology is to determine the quantity and type of DNAPL present in the subsurface and is applicable to both saturated and unsaturated soils. DNAPL contamination characterization in aquifers involves the location of DNAPL zones, and the estimation of the amounts of DNAPL within the zones. The four methods of DNAPL characterization currently available for site investigations are as follows:

1. Core sampling,
2. Cone penetrometer testing,
3. Geophysical loggings, and
4. Tracer test methods.

The limitations with core sampling, cone penetrometer testing, and geophysical logging methods involve the size of the sample with respect to the area of interest. When site characterization data indicate there is a high potential for the presence of DNAPL, Methods 1, 2, and 3 would provide limited probability of detecting DNAPL, as it is possible that the intrusive investigation could miss the location of the DNAPL pool. The advantage of NPTT is that the sample is much larger with respect to site area than the previously referenced methods.

Therefore, NPTT samples a much larger volume of porous medium than core samples or geophysical logs. Consequently, the DNAPL saturation estimated from tracer data represents an average over a larger volume.

Tracers are developed specifically for each site location. Developmental requirements include only a sample of the soils from the zone where testing will be conducted. These soil samples are then tested in a laboratory where optimal tracers and application concentrations will be determined for the full-scale site characterization test.

Although DNAPL tracer testing is a new field with respect to detection of environmental contaminants, the methods are adapted from partitioning interwell tracer tests (PITT) used in petroleum engineering. The advantage PITT has over core sampling, cone penetrometer testing, and geophysical loggings is that it is more effective in locating subsurface DNAPL pools, lenses, and residuals; can estimate the DNAPL saturation; and can provide a means of assessing the performance of DNAPL remediation systems.

Tracers can be added to fluids in low concentrations and used to follow movement without affecting the physical properties of the fluids. The partitioning interwell tracer test consists of the simultaneous injection of several tracers with different partition coefficients at one or more injection wells and the subsequent measurement of tracer concentrations at one or more production or monitor wells. When tracers with different partition coefficients are injected into the aquifer, the nonpartitioning tracers stay in the water phase (or gas phase in the case of the vadose zone), and move with the velocity of the water, while the molecules of partitioning tracers move back and forth between the water and DNAPL phases. When the tracer molecules are in the water phase, the molecules move with the velocity of the water, and when in the DNAPL phase, move with the velocity of the DNAPL. If the DNAPL is at residual saturation, the tracer molecules move only in the water phase. The net result is that the partitioning tracer pulse lags behind the nonpartitioning tracers moving with the water front. The extent of the separation of the tracer pulses depends on the fraction of time the tracer is in the DNAPL phase compared to that in the water, which is a function of DNAPL saturation and the partition coefficient. The greater the chromatographic separation of the tracers, the greater the DNAPL saturation. Figure 3-9 presents an example of the tracer test response showing tracer eluting at different times, for a simulated aquifer contaminated with PCE. By analyzing the production well tracer response, the amount of residual DNAPL in the subsurface environment can be determined. A simple method for analyzing the tracer response is the method of moments (Himmelblau, 1968), which can be

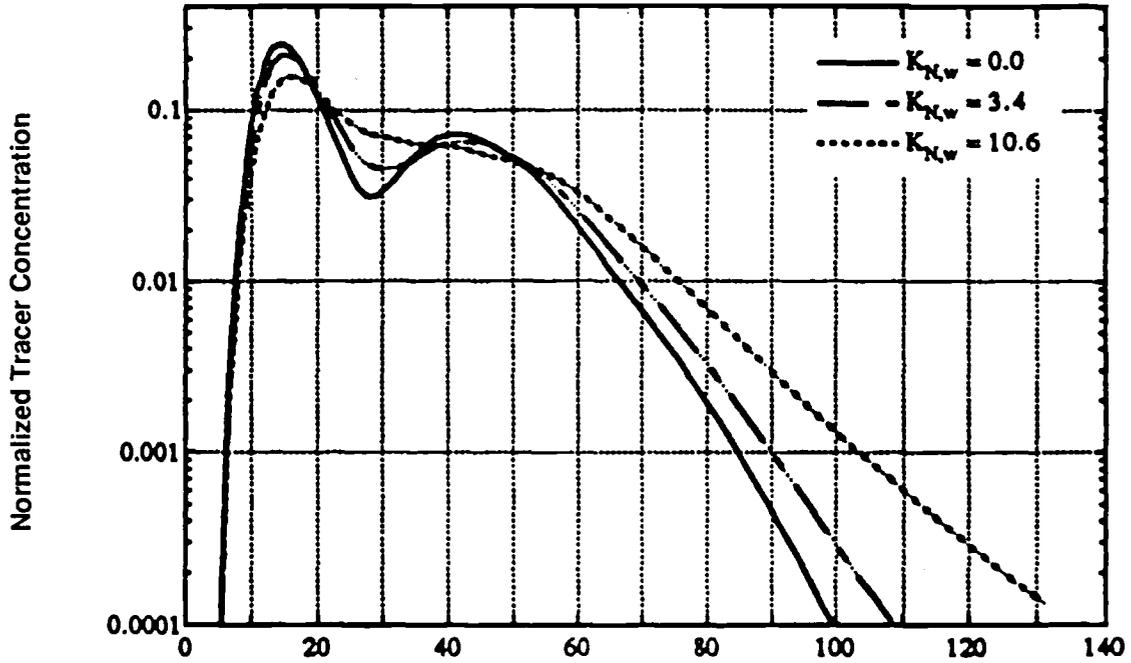


Figure 3-9
PRODUCTION WELL TRACER RESPONSE
CURVES BEFORE SURFACTANT REMEDIATION

SOURCE: ESE, 1994.



Environmental
Science &
Engineering, Inc.

A CILCORP Company

used to estimate the level of DNAPL between an injection and extraction well in an interwell test (or in the radius of a single well using a single well test). Jin, *et al.* (1994) provides the specific numerical methods used to analyze and interpret the data.

NPTT can also be used to assess the effectiveness of a DNAPL remediation program similarly to that used to detect DNAPL during the characterization phases of a project, provided the level of DNAPL present had been quantified prior to remediation. Specifically, if pre-remediation DNAPL levels are known, the degree of treatment to date can be assessed. If pre-remediation DNAPL levels are not known, the tests are still useful in that they can be used to quantify how much DNAPL remains in the subsurface.

Partitioning tracer tests can be conducted using a single-well (Figure 3-10), in which the area near the well is flooded with a solution containing the tracer. After flooding, water is extracted from the well and chemical analysis is performed to quantify the concentrations of tracer present. With the interwell method (Figure 3-11), the tracer is injected into the injection wells and extracted using extraction wells. Water from the extraction well(s) is analyzed using the same methods for water from the single well test.

Both well methods have been used extensively in the petroleum industry to estimate residual oil saturation prior to the beginning of enhanced oil recovery operations. Single-well tests have been applied to over 300 oil field reservoirs throughout the world in a variety of settings. The strengths and weaknesses of the tests have been determined, and the latter remedied by improved tracers and hydraulic designs. However, the conventional application of single-well tracer test technology to aquifers has the principal drawback of geophysical loggings and coring, namely, that the single well must penetrate very close to a DNAPL contamination area for the method to be effective. Consequently, the Intera, Inc. (Intera)/University of Texas at Austin (UT) team has concentrated research on

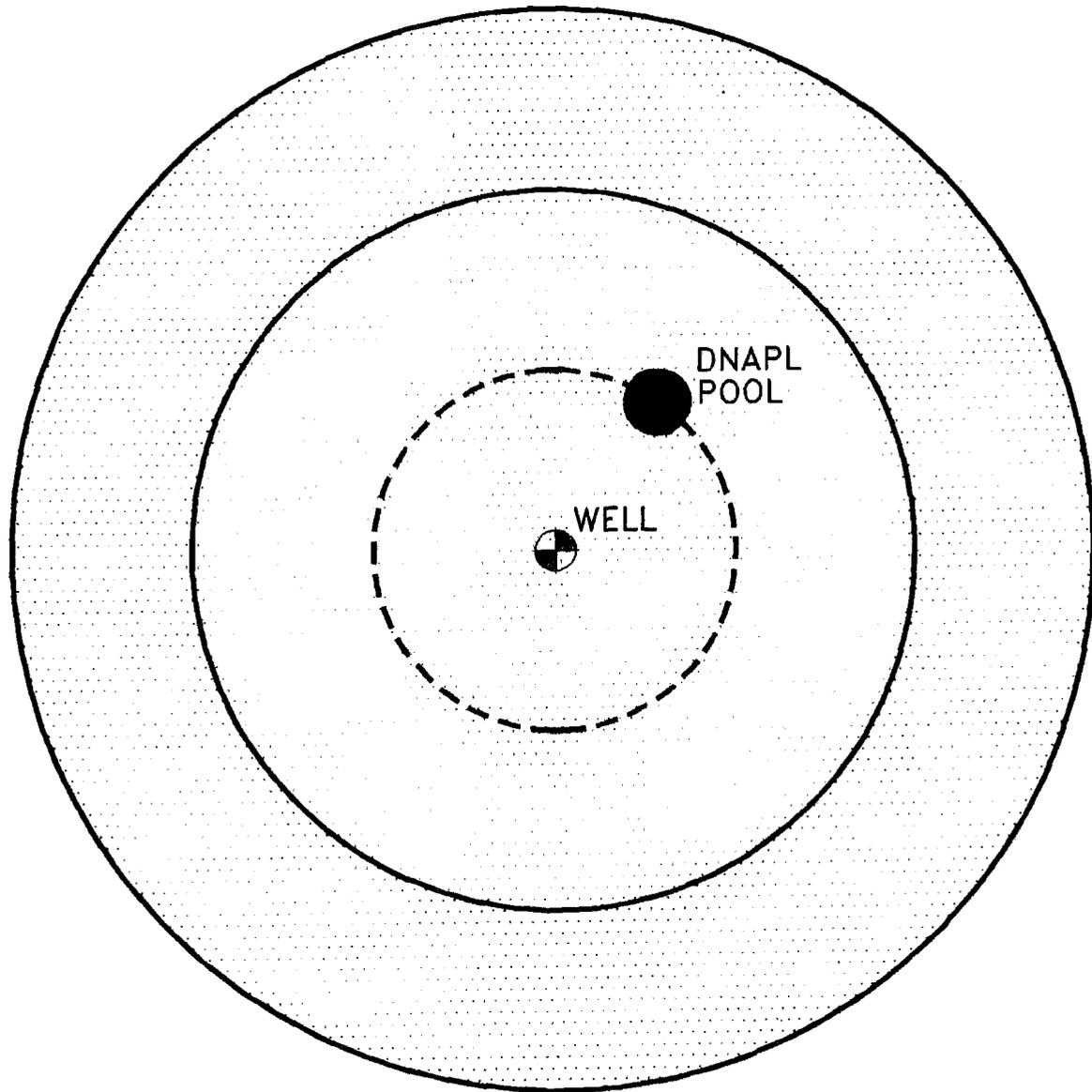


Figure 3-10
SINGLE-WELL PARTITIONING TRACER TEST
AFP4 AND CAFB
FORT WORTH, TEXAS
SOURCE: ESE, 1994.



Environmental
Science &
Engineering, Inc.

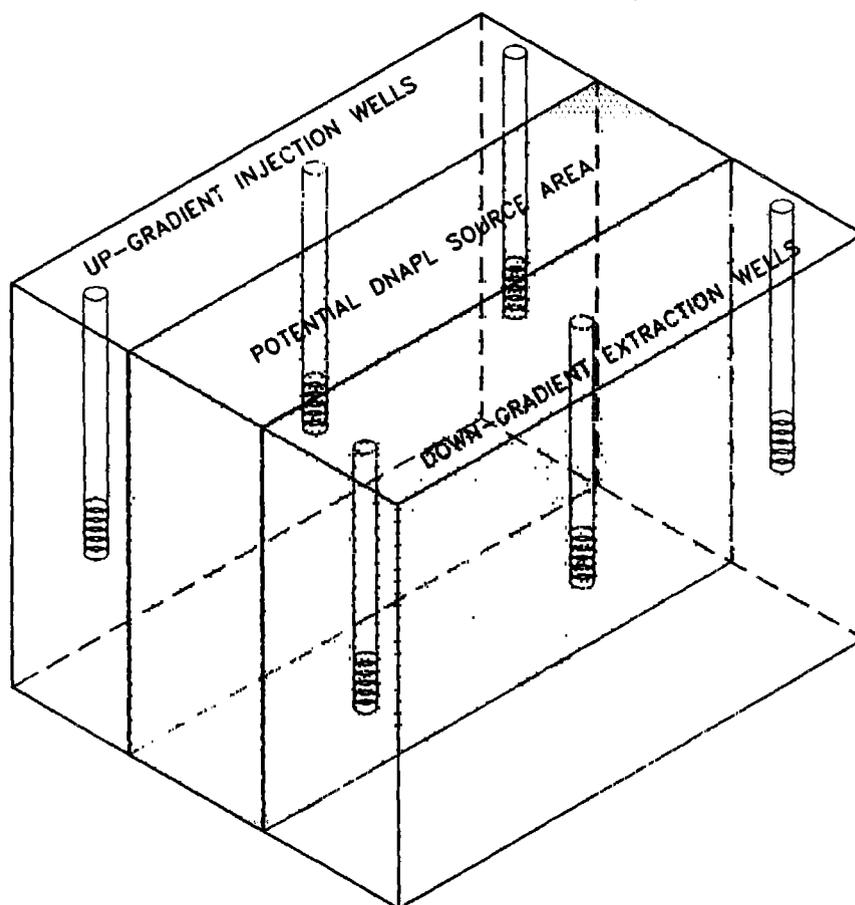


Figure 3-11
POTENTIAL PARTITIONING CONFIGURATION
OF INTERWELL PARTITIONING TRACER TEST
AFP4 AND CAFB, FORT WORTH, TEXAS
SOURCE: ESE, 1994.



Environmental
Science &
Engineering, Inc.

interwell partitioning tracer tests. With both well methods, the wells must be screened in the layer where the DNAPL is present for the tracer to interact with the DNAPL and provide meaningful and useful data.

3.9.2 APPLICABILITY

The partitioning tracer testing technology is in its infancy with respect to application in the environmental field. However, it is a well developed technology in the petroleum engineering field, and is expected to be useful in detecting DNAPL phases at contaminated sites. The challenge of locating DNAPL at a contaminated site has previously been a hit-or-miss exercise with low success. Consequently, the focus of remedial action has historically been on the dissolved contaminant in the water, not on DNAPL. This has resulted in inefficiently designed systems that will actually require more time to achieve remedial objectives than anticipated in the remedial design, due to the lack of information regarding DNAPL. The tracer characterization technology offers, for the first time, a scientific and feasible means of locating DNAPL.

3.9.3 LIMITATIONS

Tracers are developed site specifically. Some tracers contain chemicals that are regulated by EPA and state agencies and could cause concern to regulatory agencies with respect to additional input of contamination to the subsurface. Although the levels of tracer input are extremely low, and most are biodegradable, there may be a degree of concern on the part of regulatory agencies regarding possible additional water quality degradation imparted by the test.

The success of this technology depends on achieving a tracer path through the potential DNAPL zone. Well placement and screen intervals are critical parameters in testing. If wells and/or screens are not properly placed to achieve a tracer path through the DNAPL, the DNAPL will not be detected.

As previously stated, the technology is new; therefore, results from previously conducted full-scale tests are not available.

3.9.4 PROTOTYPE INSTALLATIONS

To date, there are no operable prototype installations. However, the Intera/UT team will perform testing at two sites during the summer of 1994. One test will be conducted at Sandia National Laboratories (Albuquerque, New Mexico) and will use an interwell test in the unsaturated zone to estimate the quantity of DNAPL. This test is scheduled to begin July 18, 1994.

A second test, also during the summer of 1994, will be conducted at the DOE facility in Paducah, Kentucky. This will be a single-well test conducted in the saturated zone.

3.9.5 RESULTS ACHIEVED

No information is currently available regarding results achieved at prototype installations. Information related to testing conducted at the sites described in Section 3.9.4 is expected to be available in September 1994.

3.9.6 APPLICABILITY TO THE STUDY AREA

The AFP4/CAFB team has concluded that it is probable that DNAPL is present at the Window Area of AFP4. Partitioning tracer tests can be performed at this location to estimate the amount of DNAPL present, and to better focus the efforts of the groundwater FS. The testing can also provide more accurate information for use in estimating remediation time and costs. The test is also applicable to the unsaturated soils beneath Building 181, where testing can be used to optimally locate extraction wells. These data can be used to estimate the level of remediation (and associated costs) remaining.

A detailed itemized cost to implement this technology could not be prepared due to the early developmental stage of this method. However, Intera estimates that

224086

initial testing of the Window Area may cost approximately \$300,000 for a single test. Although, due to economics of scale associated with the wells installed and the mobilization of field equipment and personnel, subsequent tests could be performed for significantly less. Vadose zone NPTT beneath Building 181 is estimated (by Intera) to cost approximately \$80,000.

4.0 CONCLUSIONS

Treatment technologies for the remediation of TCE-contaminated groundwater at the study area are evaluated in this Task 4 report. Technologies considered in the 1993 FS are evaluated in Section 2.0; potential alternative technologies are evaluated in Section 3.0 and the Appendices.

Based on the technology evaluation, four treatment technologies, one recovery technology, and one characterization technology were recommended for the remediation of groundwater at the study area. They include: (1) air stripping, (2) NAPL partitioning tracer testing, (3) UV/H₂O₂, (4) horizontal well air sparging, (5) horizontal well biosparging, and (6) DNAPL recovery using surfactants and tracer testing.

Promising technologies that were evaluated but not selected include in-situ bioremediation and metal-enhanced-in-situ degradation. These two technologies were field tested for the remediation of TCE-contaminated groundwater at CFB, Borden. The in-situ bioremediation technology was unsuccessful in degrading TCE. Metal-enhanced in-situ degradation technology was successful in degrading TCE; however, degradation products (i.e., DCE, vinyl chloride) were observed downgradient of the reactive metal wall. Further development is required on these two technologies for successful application to the remediation of TCE-contaminated groundwater.

The following four treatment technologies were also considered for application to the study area: (1) titanium dioxide catalytic oxidation, (2) two-stage methanotrophic biodegradation, (3) high-energy electron beam irradiation, and (4) ultrasonic detoxification.

The titanium dioxide oxidation technology was field tested at SRS in 1992. Several field runs were conducted and varying TCE destruction efficiencies

(60 to 98 percent) were observed. Further development is required to obtain consistency in the destruction efficiencies. Biotrol, Inc., conducted a pilot test on the two-stage methanotrophic biodegradation technology for degrading TCE in groundwater. During the initial runs, higher TCE destruction efficiencies (89 percent) were observed; however, due to the instability of the microbial culture, the pilot test was unsuccessful. Reaction byproducts (i.e., formic acid, formaldehyde, and acetaldehyde) were formed during the high-energy electron beam irradiation pilot test. Therefore, further development of this technology would be necessary for application to the remediation of TCE-contaminated groundwater. Ultrasonic detoxification technology has not been tested for the destruction of TCE in groundwater.

A summary of each technology, as evaluated in this report, is presented in Table 4-1.

TABLE 4.1 TECHNOLOGY SUMMARY TABLE

TECHNOLOGY	APPLICABILITY	LIMITATION	PROTOTYPE INSTALLATION	RESULTS ACHIEVED	APPLICABILITY TO THE STUDY AREA	COSTS (X \$1000)
TECHNOLOGIES CONSIDERED IN THE FS						
Air stripping	removal of VOCs from wastewater	may require off-gas treatment	well established technology, numerous full-scale installations	greater than 99% removal efficiencies	applicable	(1) \$1,600
UV/H ₂ O ₂	removal of organic compounds from wastewater	may require bench/pilot test and pretreatment	Sacramento Army Depot (SAD) and several other sites	greater than 95% destruction efficiency at SAD	applicable	(1) \$3,000
Biological treatment	bio-degradation of organic compounds from wastewater	long-term effectiveness was not observed.	1) Tinker AFB, 2) DOE Savannah River Site	approx. 80% biodegradation of TCE at Tinker AFB and 99% at the DOE site	not applicable; stability of TCE degrading microorganisms was not observed over a long period of time	(2)
Dense non-aqueous phase liquid (DNAPL) recovery	enhanced removal of DNAPL from groundwater	geologic heterogeneity may prevent thorough contact of surfactant with DNAPL	none reported; application to hazardous waste remediation is in infancy	none	applicable	(3)
ADDITIONAL TECHNOLOGIES						
In-situ bioremediation	In-situ biodegradation of organic compounds in groundwater	sections of the plume may have to be controlled or captured by other means	Canadian Forces Base (CFB) Borden Toronto, Canada	unsuccessful in degrading TCE	not applicable; field tests were unsuccessful in degrading TCE	(2)
Metal-enhanced In-situ degradation	In-situ degradation of organic compounds in groundwater	reaction mechanism, persistence of the reaction over long-term periods, and effect of other chemicals are unknown	CFB Borden, Toronto, Canada	approx. 90% TCE biodegradation; however DCE was detected in excess of MCL as reaction by-product.	not applicable; intermediate degradation products (e.g. DCE) were observed; reaction mechanism was not understood, and the long-term integrity of the well was not observed	(2)
Horizontal well air sparging with permeable In-situ barrier	extraction of organic compounds from groundwater and soils	site-specific geologic conditions (e.g., soil permeability, heterogeneity prevent effective treatment except in the permeable barrier	DOE Savannah River Site (air sparging only without permeable barrier)	TCE concentration in groundwater was reduced from 1600 to 10 µg/L	applicable; adequate contact between air and water and reliable recovery of contaminated air can only be achieved in this channelized aquifer by construction of an artificial granular treatment zone or "permeable barrier"	(2) \$7,900
Horizontal well biosparging	extraction and In-situ biodegradation of organic compounds from groundwater and soils	site-specific geologic conditions (e.g., soil permeability, heterogeneity may complicate the use of this technology	1) DOE Savannah River Site 2) Moffett NAS	1) At the DOE Site, methane injection was effective in degrading TCE in groundwater and soil no results are available. 2) At the Moffett NAS methane injection produced encouraging results in degrading TCE.	applicable; this technology cannot be used as a sole remedy, but can reduce the duration of pump-and-treat remediation by removing contamination in source areas	(5) \$2,800
Titanium dioxide catalytic oxidation	destruction of organic compounds in water and air	further development required to achieve consistent TCE destruction efficiencies	1) DOE Savannah River Site, 2) Tyndall Air Force Base	TCE destruction efficiencies between 60 - 98% were observed at DOE site, 50-75% for BT EX at TYAFB	not applicable; consistent TCE destruction efficiencies were not observed; less efficient than UV/H ₂ O ₂ technology; requires high capital and O&M cost	(1,4) \$11,500
Two-stage methanotropic biodegradation	biodegradation of organic compounds in groundwater	growth and stability of microorganisms is not achieved	BioTrol, Inc., Eden Prairie, Minnesota	TCE biodegradation efficiency was 89%, variability in TCE degradation efficiency and instability in microbial cultures were observed	not applicable; the best test was unsuccessful in maintaining growth & stability of TCE degrading microorganisms	(2)
High-energy electron beam irradiation	destruction of organic compounds in groundwater; the technology needs further development to minimize the formation of reaction by-products in the effluent.	formation of reaction by-products as a result of irradiation of TCE-contaminated groundwater	Electron Beam Research facility, Miami, Florida	formic acid, formaldehyde, and acetaldehyde formed as reaction by-products	not applicable; reaction by-products formed during TCE degradation; requires high capital and O&M costs	(2)
Ultrasonic Detoxification	destruction of chlorinated organic compounds in groundwater; the technology needs to be developed for TCE-destruction at both bench and pilot-scale levels.	no data on TCE; further development required	Argonne National Laboratory, Illinois	none observed on TCE	not applicable; no tests were run for TCE degradation; requires further development	(2)
DNAPL Partitioning tracer testing (NPPT)	Characterize location and quantity of DNAPL	New developmental technology; achieve tracer path through DNAPL	1) Sandia National Laboratories 2) DOE at Paducah, KY	Pending; prototype installations operable in Summer 1994	applicable	\$300,000 (Window Area) \$80,000 (Bldg. 181 Vadose Zone)

Notes:

- (1) Costs are based on a 30-year treatment period at a 5% interest rate.
- (2) Costs are not developed when the technology is not applicable.
- (3) Limited information is available to develop for comparison to UV/H₂O₂ technology.
- (4) Although not applicable, costs are developed for comparison to UV/H₂O₂ technology.
- (5) Costs are based on a 5-year treatment period at a 5% interest rate and an assumed 50% reduction in duration of treatment by air stripping (15 years).

Source: ESE

APPENDIX A
TRIP REPORTS

TRIP REPORT
UNIVERSITY OF WATERLOO
ONTARIO, CANADA

A.1.1 SITE VISIT

The University of Waterloo is developing in-situ treatment technologies for the remediation of groundwater contaminated with organic compounds. Canadian Forces Base (CFB) Borden has been selected as the site for the field testing of the innovative technologies. The University of Waterloo has been operating a field study using metal-enhanced in-situ degradation technology and in-situ bioremediation technology at the CFB Borden. A site visit was conducted by Dr. Prasad Kuchibhotla, P.E., of Environmental Science & Engineering, Inc. (ESE). The purpose of the visit was to investigate the applicability of the in-situ technologies for the remediation of groundwater in the study area at AFP4, Fort Worth, Texas.

During the site visit, Dr. Kuchibhotla met with Mr. John L. Vogan, Envirometal Technologies, Inc.; Stephanie F. O'Hannesin and Dr. Robert W. Gillham, University of Waterloo; and Robin Jowett, Waterloo Groundwater Control Technologies, Inc.

A.1.2 OBSERVATIONS

A.1.2.1 METAL-ENHANCED IN-SITU DEGRADATION

With this technology, several chlorinated organic compounds (e.g., CCl_4 , hexachloroetheane, tetrachloroethene, and TCE) were successfully degraded during column tests at the University of Waterloo. The effectiveness of several metals (ex: iron, zinc, copper, brass, and aluminum) for the degradation of these compounds was also evaluated (Gillham, 1992). Based on the column studies, iron fillings were selected as the most efficient reducing agent for the chlorinated compounds.

The field study of this technology was initiated in May 1991 at CFB Borden. The aquifer material at the site is a medium to fine sand, and the average groundwater velocity is approximately 9 cm/day. The direction of groundwater flow varies seasonally by approximately 30°. TCE was selected as the contaminant for remediation in groundwater. TCE introduced into the groundwater as part of a previous study was used as the source of contamination for this study.

The source of the plume was located 4.0 m below the ground surface and 1.0 m below the water table. The plume was about 2 m width and 1 m thick, with maximum concentrations along the axis of approximately 250,000 $\mu\text{g/L}$ of TCE and 43,000 $\mu\text{g/L}$ of tetrachloroethene (PCE).

A pilot-scale system, consisting of a permeable wall and several monitor wells were installed at the site. The permeable wall was installed at 5 m downgradient from the source and across the flow path of the TCE contaminated plume. It consisted of iron fillings and sand. The wall was constructed by driving sheet piling to form a cell 1.6 m wide and 5.5 m long. The native sand was replaced by the reactive material, consisting of 22 percent by weight iron grindings and 78 percent by weight concrete sand. The concrete sand, which was coarser than the native materials, was used to insure that the wall would be more permeable than the surrounding sand. After the reactive mixture was installed, the sheet piling was removed, allowing the contaminant plume to pass through the wall.

The wall was designed based on the results of the column studies. The thickness was estimated from the half-life of TCE, groundwater velocity, and initial and target concentrations of TCE. The results of column studies yielded a half-life of 15 hrs for TCE and PCE. Therefore to degrade TCE from 250,000 to 5 $\mu\text{g/L}$ would require about 16 half-lives or $15 \times 16 = 240$ hrs. To achieve a residence time of 240 hrs, at a flow rate of 9 cm/day, the wall would have to be 90 cm

thick. Because of the lower initial concentration and similar half-life, it is expected that the thickness of the wall would be sufficient to degrade PCE as well.

A containment wall consisting of sealable steel sheet piling, referred to as "Funnel-and-Gate System," was built immediate down-gradient of the contaminated plume to control the width of the plume. Also, several groundwater monitor wells were installed upgradient and downgradient of the wall to monitor the degradation of TCE in groundwater. A total of 348 sampling points were installed. Monitoring was frustrated by the narrow character of the plume and the changing flow direction (Photograph A-1.1).

The effectiveness of the system was observed by analyzing the TCE and the degradation products (e.g., DCE and vinyl chloride) in the down-gradient wells. Over the 474 day monitoring period, there was no evidence of a decline in the effectiveness of the wall in degrading the TCE and PCE. Concentration distributions through the wall were determined on 13 occasions over this period. It was observed that most of the TCE degradation occurred within the first 50 cm of the wall, which corresponds to a residence time of about 5 days or eight half-lives. In eight half-lives, TCE would degrade from 250,000 $\mu\text{g/L}$ to about 1,000 $\mu\text{g/L}$. This is lower than the measured concentration of 25,000 $\mu\text{g/L}$ for TCE. The downstream concentrations are about three orders of magnitude greater than the MCLs.

Based on the results, it appears that upstream portion of the wall performed in a manner consistent with the column studies. At greater distance from the wall, the performance was not clearly below that expected. The reason for this performance is uncertain.

A.1.2.2 IN-SITU BIOREMEDIATION

In this process, a permeable injection wall capable of introducing dissolved substances into an aquifer is built across the path of a contaminated plume. Groundwater is extracted, mixed with nutrients, and injected back into the ground. After the nutrients are introduced into the ground, the nutrient-pulse is permitted to drift into the groundwater under natural gradient conditions. The cycle is repeated at intervals of weeks or months.

The in-situ bioremediation field evaluation is currently in progress at the CFB Borden. A permeable wall 1 m thick, 4 m deep, and 4 m long was installed at the field test site. Experiments were conducted in which carbon tetrachloride (CCl₄) and TCE were injected into the upstream of the wall; water within the wall was periodically amended with acetate.

The final results of the study are not still available. However, during a phone conversation with a project member at the University of Waterloo, the initial studies indicated that this technology was successful in degrading CCl₄ in groundwater. However, it was unsuccessful in degrading TCE in groundwater. Further studies are underway to determine the effectiveness of this technology for TCE in groundwater.

A.1.3 CONCLUSIONS

In the metal-enhanced in-situ degradation technology, chloride concentration was used as a measure of the degradation of both PCE and TCE. Of both TCE and PCE are completely degraded, then the estimated chloride concentration would be 220,000 µg/L. However, the measured chloride concentration was 50 percent of the expected value. The reason for the performance is uncertain. Also, no vinyl chloride was detected in the downstream. This may also suggest that the degradation of TCE and PCE was incomplete and the intermediate degradation product (DCE) was formed due to incomplete degradation process. This may suggest that further studies may be necessary to understand the process.

Based on the information provided on the initial field results, the in-situ bioremediation technology was unsuccessful in degrading TCE (less than 10 percent degradation) in groundwater. Further studies may be necessary to determine the effectiveness of this technology for TCE remediation in groundwater.

A.1.4 RECOMMENDATIONS

The field studies using metal-enhanced in-situ degradation technology greatly reduced the TCE concentration in the downstream groundwater. However, the concentration of TCE and DCE were substantially higher than the MCL values. Further development may be necessary to understand the reaction mechanism before full-scale implementation of this process. Therefore, this technology is not considered applicable for the remediation of groundwater at the study area.

The field studies using in-situ Bioremediation technology were unsuccessful in the microbial degradation of TCE in groundwater. Therefore, this technology is not considered applicable for the remediation of groundwater at the study area.



Figure A.1-1 METAL ENHANCED IN-SITU DEGRADATION TECHNOLOGY AT CFB BORDEN



Figure A.1-2 INSITU BIOREMEDIATION TECHNOLOGY AT CFB BORDEN

UNIVERSITY OF WATERLOO PUBLICATION LIST

Q. REMEDIATION OF CONTAMINATED GROUNDWATER

224097

- Q-37: Devlin, J.F., and Barker, J.F., 1993. A semi passive nutrient injection scheme for enhanced in-situ bioremediation. Ground Water. *Box 101*
- Q-36: Devlin, J.F., and Barker, J.F., 1993. A semi passive nutrient injection system for in situ bioremediation. Engineering Hydrology, Symposium sponsored by the Hydraulics Division/ASCE, July 25-30, San Francisco, California, pp. 868-873.
- Q-35: Starr, R.C., and Cherry, J.A., 1993. In situ remediation of contaminated groundwater: The funnel-and-gate system. Ground Water (in submittal).
- Q-34: Lipczynska-Kochany, E. and Kochany, J., 1993. Electron paramagnetic spin trapping detection of free radicals generated in direct photolysis of 4-bromophenol in aqueous solution. Journal of Photochemistry and Photobiology, Vol. 73, pp. 23-33.
- Q-33: Lipczynska-Kochany, E., 1993. Degradation of aromatic pollutants by means of the advanced oxidation processes in a homogeneous phase: Versus the fenton reaction. In Chemical Oxidation: Technology for Nineties, Vol. 3, Technomic Publishing Co. Inc., Lancaster, Pennsylvania.
- Q-32: Orth, W.S., and R.W. Gillham, 1993. Mass balance of the degradation of trichloroethylene in the presence of iron filings. Paper presented at the 1993 Joint CSCE-ASCE National Conference on Environmental Engineering, Montreal, Quebec, July 12-14.
- Q-31: Gillham, R.W., O'Hannesin, S.F., and Orth W.S., 1993. Metal enhanced abiotic degradation of halogenated aliphatics: laboratory tests and field trials. Paper presented at 1993 HazMat Central Conference, Chicago, Illinois, March 9-11.
- Q-30: Rivett, M.O., 1993. A field evaluation of pump-and-treat remediation. Waterloo Centre for Groundwater Research, University of Waterloo, Waterloo, Ontario, N2L 3G1.
- Q-29: Gillham, R.W. and O'Hannesin, S.F., 1992. Metal-enhanced degradation of halogenated aliphatic compounds. (in submittal).
- Q-28: Barker, J.F., 1992. Nitrate as an alternate electron acceptor for in situ bioremediation of gasoline-contaminated groundwater. In Situ Bioremediation Symposium '92, Sept. 20-24. Niagara-on-the-Lake, Ontario sponsored by IAHS, Environ. Canada, WCGR, GASReP, WTC, NCGR, Suzanne Lesage (ed) pp 68-81.
- Q-27: Pankow, J.F., Johnson, R.L., and Cherry, J.A., 1992. Air sparging in gate wells within cutoff walls and in trenches for the control of plumes of volatile organic compounds (VOCs). Ground Water, Vol. 31, No. 4, pp. 654-663.
- Q-26: Reardon, E.J., Hobbs, M.Y., and Warren, C.J., 1992. Reduction of trace element concentrations in alkaline waste porewaters by dedolomitization. Environmental Science and Technology (in submittal).
- Q-25: O'Hannesin, S.F., and Gillham, R.W., 1992. A permeable reaction wall for in situ degradation of halogenated organic compounds. 45th Canadian Geotechnical Society Conference, Toronto, Ontario, Oct. 25-28.
- Q-24: Schnarr, M.J., and Farquhar, G.J., 1992. An in-situ oxidation technique to destroy residual DNAPL from soil. IAH Conference on Modern Trends in Hydrogeology, Hamilton, Ontario, Canada, May 10-13.

- Q-23: Gillham, R.W., and O'Hannesin, S.F., 1992. Metal-catalysed abiotic degradation of halogenated organic compounds. IAH Conference Modern Trends in Hydrogeology, Hamilton, Ontario, May 10-13.
- Q-22: Starr, R.C., and Cherry, J.A., 1992. Applications of low permeability cutoff walls for groundwater pollution control. 45th Canadian Geotechnical Conference, October 26-28, Toronto, Ontario.
- Q-21: Starr, R.C., Cherry, J.A., and Vales, E.S., 1992. A new type of steel sheet piling with sealed joints for groundwater pollution control. 45th Canadian Geotechnical Conference, October 26-28, Toronto, Ontario.
- Q-20: Kueper, B.H., Feenstra, S., Rivett, M.O., and Cherry, J.A., 1992. A series of controlled field experiments to study DNAPL behaviour: Implications for site remediation. Proceedings: HAZMAT International, Hazardous Materials and Environmental Management Conference and Exhibition, Atlantic City, NJ., June 10-12.
- Q-19: Rivett, M.O., Feenstra, S., and Cherry, J.A., 1992. Pump-and-treat remediation of a chlorinated solvent plume: A field study. Extended abstract of poster presented at the Subsurface Restoration Conference, 3rd International Conference on Ground Water Quality Research, Dallas Texas, June 21-24.
- Q-18: Burris, D.R. and Cherry, J.A., 1992. Emerging plume management technologies: In situ treatment zones. In proceedings of the 8th Annual Meeting of the Air and Waste Management Association. Manuscript 92-34.04.
- Q-17: Starr, R.C., Cherry, J.A., and Vales, E.S., 1991. Sealable joint sheet pile cutoff walls for preventing and remediating groundwater contamination. Technology Transfer Conference, MOE, Toronto, November 25-26.
- Q-16: Starr, R.C. and Cherry, J.A., 1990. In situ barriers for groundwater pollution control. Prevention and Treatment of Soil and Groundwater Contamination in the Petroleum Refining and Distribution Industry, Montreal, Quebec, Oct. 16-17.
- Q-15: McClellan, R.D. and Gillham, R.W., 1990. Vapour extraction of trichloroethylene under controlled field conditions. IAH Conference on Subsurface Contamination by Immiscible Fluids, Calgary, Alberta, April 18-20, 1990.
- Q-14: Acton, D.W., Barker, J.F., Shaw, M.A., Beaudet, F. and Cherry, J.A., 1989. The mobility and persistence of selected organic solutes in anaerobic groundwaters and possible in situ remediation measures. Proceedings MOE Technology Transfer Conference, 1989, Part C, Liquid and Solid Waste Research, pp. 1-8.
- Q-13: Lemon, L.A., Barbaro, J.R., and Barker, J.F., 1989. Biotransformation of BTEX under anaerobic denitrifying conditions: Evaluation of field observations. Proceedings of the FOCUS Conference on Eastern Regional Ground Water Issues.
- Q-12 + + : Allen, R.M., Gillham, R.W., and Barker, J.F., 1989. Rehabilitation of Groundwater: Removal of soluble petroleum constituents through soil application. Prepared for the American Petroleum Institute.
- Q-11: Berwanger, D.J. and Barker, J.F., 1989. Aerobic biodegradation of aromatic and chlorinated hydrocarbons commonly detected in landfill leachates. Water Poll. Res. Jour. Canada, 24 pp.
- Q-10: Acton, D.W., Barker, J.F., and Mayfield, C.I., 1989. Enhanced in situ biodegradation of aromatic and chlorinated aliphatic compounds in a leachate-impacted aquifer. Proc. NWWA 3rd National Outdoor Action Conf. and Exposition, Orlando, Fl., May 22-25, 1989.

Acton, D.W. and Barker, J.F., 1989. Enhanced biodegradation of aromatic compounds in North Bay aquifer material. Jour. Contam. Hydrology (in revision).

224099

- Q-08: Berry-Spark, K.L., Barker, J.F., and Mayfield, C.I., 1989. The design and evaluation of in situ bioremediation methods for the treatment of sludges and soils at waste disposal sites. MOE Environmental Research Report (ISBN: 0-7729-5652-9), 18 pp.
- Q-07: Mackay, D.M. and Cherry, J.A. Groundwater contamination: Limitations of pump-and-treat remediation. Environmental Science & Technology, Vol. 23, No. 6, pp. 630-636.
- Q-06: Major, D.W., Mayfield, C.I. and Barker, J.F., 1987. Biotransformation of benzene, toluene and xylenes (BTX) under denitrifying conditions in shallow aquifer material. Ground Water, Nov/Dec. issue.
- Q-05: Berry-Spark, K.L. and Barker, J.F., 1987. Nitrate remediation of gasoline contaminated groundwaters. Results of a controlled field experiment. Proc. of Petrol. Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection and Restoration. NWWA/API, Houston, Nov. 17-19, 1987, in press.
- Q-04: Berry-Spark, K.L., Patrick, G.C., Barker, J.F., Major, D. and Mayfield, C.I., 1987. The influence of other gasoline derived organics on the behaviour of dissolved monoaromatics in ground water. Proc. 4th Annual Eastern Regional Ground Water Conf., July 14-16, 1987. Nat. Water Well Assoc., pp. 665-680.
- Q-03: Allen, R.M., Gillham, R.W. and Barker, J.F., 1987. Remediation of gasoline-contaminated ground water by infiltration through soil. Proc. 4th Annual Eastern Regional Ground Water Conf., Burlington, Vermont, July 14-16, Nat. Water Well Assoc., pp. 681-698.
- Q-02: Harrison, E.M. and Barker, J.F., 1987. Sorption and enhanced biodegradation of trace organics in a groundwater reclamation scheme - Gloucester site, Ottawa, Ontario. Journal Contaminant Hydrogeology, Vol. 1, pp. 349-373.
- Q-01: Berry-Spark, K. and Barker, J.F., 1986. Remediation of gasoline-contaminated groundwaters: A controlled field experiment. Proc. Petrol. Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection and Restoration - A Conf. and Exposition; NWWA/API, Houston, Nov. 12-14, 1986, pp. 160-177.
- Q-00: Farquhar, G.J., 1977. Leachate treatment by soil methods. Management of Gas and Leachate in Landfills, Proceedings of the Third Annual EPA Municipal Solid Waste Research Symposium, St. Louis, Missouri, 1977.

**TRIP REPORT
SACRAMENTO ARMY DEPOT
SACRAMENTO, CALIFORNIA**

A.2.1 SITE VISIT

TCE has been used in the past at the Sacramento Army Depot (SAD) and it is the primary contaminant in the groundwater. The SAD has installed a full-scale ultraviolet light/hydrogen peroxide (UV/H₂O₂) system at the South Post site and a pilot-scale groundwater air sparging (in-situ air stripping) system at Parking Lot 3. Both these systems have been built for the remediation of TCE contaminated groundwater. The UV/H₂O₂ system has been operational for the past three years and the air sparging system has been operational since December 1993. A site visit was conducted by Dr. Prasad Kuchibhotla, P.E. of Environmental Science & Engineering, Inc. (ESE). The purpose of the visit was to investigate the applicability of the UV/H₂O₂ and air sparging technologies for the remediation of groundwater in the study area at AFP4, Fort Worth, Texas.

During the site visit, Dr. Kuchibhotla met with Mr. Danny E. Oburn, Environmental Protection Specialist and Mr. Robert Lodato, Project Manager, both of SAD. A tour of the sites was conducted by Mr. Lodato, during which Mr. Lodato explained the features and operation of the UV/H₂O₂ system and air sparging system.

A.2.2 OBSERVATIONS

A.2.2.1 UV/H₂O₂ SYSTEM

The UV/H₂O₂ treatment system, referred to as the "South Post Groundwater Treatment System," receives TCE contaminated groundwater from the South Post area. The groundwater at the site has become contaminated with approximately 65 µg/L TCE. The site stratigraphy consists of sandy soils. Bench-scale studies of the UV/H₂O₂ system were conducted by Kleinfelder, Inc. The studies were conducted to optimize the UV light intensity and H₂O₂ dosage rates to the treatment system. Based on these studies, a power setting of 60 KW and H₂O₂

feed rate of approximately 10-20 mg/L were selected for the full-scale treatment system.

The full-scale treatment system was designed to reduce TCE concentration in groundwater from approximately 100 $\mu\text{g/L}$ to an MCL of 5 $\mu\text{g/L}$. The major components of the treatment system include a H_2O_2 feed tank, an inline static mixer, and a UV/ H_2O_2 reactor. The reactor consists of two chambers of UV lamps, each chamber consisting 12 lamps. The lamp power is varied manually by turning the lamps off and on from the control panel. (Photograph A.2-1). Flow rate to the treatment system was set and held constant at 360 gallons per minute (gpm).

The treatment system was designed to achieve 95% destruction of TCE at the design influent concentration of 100 $\mu\text{g/L}$ and the maximum allowable effluent concentration of 5 $\mu\text{g/L}$. The system has been successfully achieving the goal of the target effluent concentration for TCE during the entire operation.

The maintenance of the system include replacement of the UV lamps and charging H_2O_2 to the feed tank. The UV lamps are replaced approximately once in every 2-3 months. When the influent concentration of TCE changes, the dosage of H_2O_2 is changed manually by adjusting the injection pump speed to precalibrated settings to deliver a known concentration. The control panel located at the treatment system regulates the feed rate of H_2O_2 at a preset concentration. The UV lamps are switched off and on manually at the control panel. The labor requirement to maintain the system is approximately 2-3 hrs per week. Since there are two chambers for UV lamps, the flow is switched between the two chambers whenever there is a need to replace the UV lamps. Therefore, the system has been maintained without any downtime for maintenance.

A.2.2.2 AIR SPARGING

The soils at the site are typically fine, sandy loams, and permeable. Based on the site characterization data at SAD Parking Lot 3, air sparging has been proposed for the extraction of TCE contaminated vapors from groundwater. Following the extraction of contaminated vapors, the offgas is treated by PURUS air treatment system where they are adsorbed on beds of specially formulated carbonaceous resins.

The extraction and offgas treatment system has been installed and operational since December 1993. The extraction system consists of 4 shallow venting wells and 6 deep venting wells for the vacuum extraction of contaminated vapors; 6 sparging wells for air; a 10-HP air compressor, and two 600 cfm blowers.

The treatment system consists of a water separator, adsorption and desorption bed of carbonaceous resin, a low temperature and a high temperature chiller, nitrogen tank, holding tank, and vapor-phase GAC unit.

The process involves one resin bed adsorbing influent vapor while a second bed desorbing TCE (PURUS, Inc., 1994). The beds are automatically switched back and forth between adsorption and desorption cycles. The desorption cycle utilizes a combination of temperature, pressure, and nitrogen purge gas. During the adsorption cycle, TCE in the vapor is adsorbed on the bed. In the desorption cycle, the bed is heated to 250 degrees Celsius under vacuum to drive off adsorbed TCE. The vapors are condensed and the condensate (TCE) is collected and recovered as a liquid-phase. The uncondensed vapors are further treated using vapor-phase GAC units. The vapor-phase GAC units are designed to treat the entire contaminated vapor stream from the venting wells. Photograph A.2-2 presents the treatment system at SAD.

A.2.3 CONCLUSIONS

The UV/H₂O₂ system has been very successful at the South Post area. There is not enough data to evaluate the performance of the pilot-scale air sparging and offgas treatment system. The estimated date of completion of the pilot-scale study of this system is Summer 1994. Mr. Lodato indicated that no data on the performance of the system will be released to public until the pilot-scale studies on the system are complete. However, Mr. Lodato verbally reported that the system recovered approximately 455 lbs of TCE.

A.2.4 RECOMMENDATIONS

The UV/H₂O₂ system at SAD has been operating successfully without a pretreatment system. No data has been provided on the physical parameters of the groundwater at SAD. However, Mr. Lodato stated that the groundwater at SAD has very low levels of total dissolved solids (TDS), total suspended solids (TSS) and iron. As a result, these parameters were not studied during the bench-scale studies and no pretreatment system was installed at the site. Also, total dissolved solids (TDS) in groundwater may potentially reduce the effectiveness of the system. TDS compete with TCE in groundwater for the hydroxyl radicals generated by H₂O₂ and the UV radiation emitted by the UV lamps.

The levels of TCE in groundwater is approximately 70 µg/L. However, higher levels of TCE (1.8 mg/L; Source: RI, 1993) are anticipated in the groundwater at the study area. The UV/H₂O₂ technology is potentially applicable at the study area; however, a bench-scale study would be necessary for the design of a full-scale system.

The study area consists of 3 to 5 foot thick surface layer of granular material (possibly fill), underlain by a 15 foot thick layer of "terrace alluvial material... composed of heterogeneous interbedded clay, silt, sand, and gravel" (Feasibility Study Report, page 1-19) and two limestone strata. Air sparging alone has a low

probability of success because majority of the contaminant is present in and below the terrace deposits, which act as an aquitard. Intensive aeration would probably built up air pockets in the limestone and drive groundwater away from the sparging well(s).

There is not enough information available from the site visit to evaluate the effectiveness of the PURUS offgas treatment technology for the remediation of TCE contaminated groundwater. Therefore, no recommendations are made about the applicability of this technology at the study area.

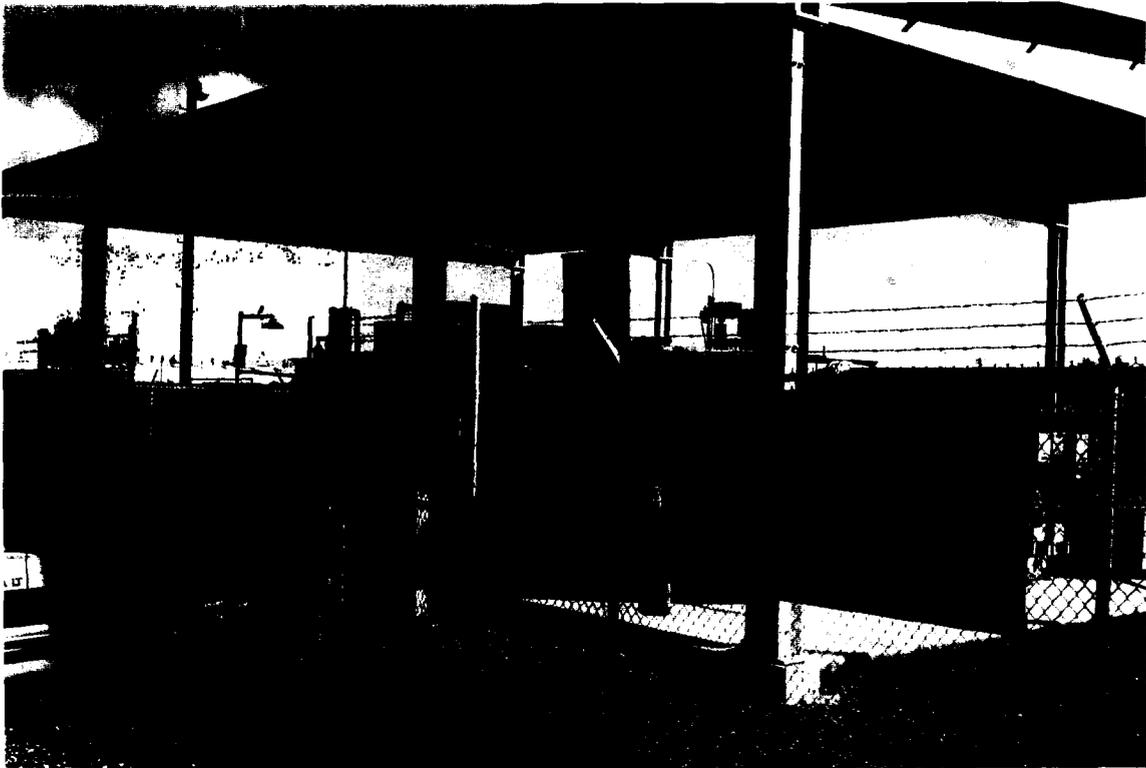


Figure A.2-1 UV/H₂O₂ TREATMENT SYSTEM AT SAD



Figure A.2-2 AIR SPARGING SYSTEM AT SAD

TRIP REPORT
DOE SAVANNAH RIVER SITE
AIKEN, SOUTH CAROLINA

A.3.1 SITE VISIT

The U.S. Department of Energy Savannah River Site (SRS) has been designated as an "Integrated Demonstration Site" for the purposes of demonstrating the feasibility of innovative technologies and enhancements to standard technologies for the removal of chlorinated VOCs from soil and groundwater. SRS has installed a full-scale in-situ volatilization (ISV) and groundwater sparging (in-situ air stripping) system at the Area-M wastewater lagoon closure site. The system has been constructed using innovative horizontal-well technology and has been used as a test bed for ISV and sparging enhancements such as electrical resistance and radio-frequency (RF) heating of soils and biological degradation by the addition of gaseous-phase nutrients. A site visit was conducted by Gary Wise, P.E. of Environmental Science & Engineering, Inc. (ESE). The purpose of the visit was to investigate the applicability of air sparging and biological enhancement of ISV to groundwater and source soils in the study area at AFP4, Fort Worth, Texas.

During the site visit, Mr. Wise met with Mr. Brian Looney and Mr. Mark Goodell of Westinghouse Savannah River Company and Mr. Ken Lombard of Bechtel Environmental, Inc. A tour of the Area-M site was conducted by Mr. Looney, during which Mr. Lombard explained the features and operation of the ISV/sparging system and biological enhancements and Mr. Looney explained the test procedures for the thermal enhancements.

A.3.2 OBSERVATIONS

A.3.2.1 AIR SPARGING SYSTEM

The former wastewater lagoons, referred to as the "Area-M Basins," received wastewater contaminated with high concentrations of the degreasing solvents trichloroethene (TCE) and tetrachloroethene (PCE). The groundwater beneath

the lagoons had become contaminated with up to 14,000 $\mu\text{g/L}$ TCE and 280 $\mu\text{g/L}$ PCE. Vadose zone soils contained up to 50 $\mu\text{g/g}$ TCE and trace levels of PCE. The site stratigraphy consists of sandy soils interspersed with clay lenses. Detailed site investigation has revealed that the majority of VOCs in soil is adsorbed into the clay lenses (see page 4 of Attachment 1, "Cleanup of VOCs in Non-Arid Soils - The Savannah River Integrated Demonstration, " for a pictorial representation). Air sparging demonstration tests, injecting sparging air into the aquifer and extracting contaminated vapors from the vadose zone, were conducted from July to December of 1990. A complete description of the system and test results is provided in Attachment 2, "Full Scale Field Test of the In-Situ Air Stripping Process at the Savannah River Integrated Demonstration Test Site (U)."

The system consists of two horizontal wells, a lower air sparging injection well and an upper vapor extraction well, installed using modified utility boring equipment (Figure A.3-1). The lower well is approximately 300 feet long, is installed in the water table at a depth of approximately 140 ft-bgs, and is constructed of slotted polyethylene pipe. The upper well is approximately 200 feet long, is installed in the vadose zone at a depth of approximately 50 feet bgs, and constructed of the same material as the lower well. The air injection rate was varied over three levels during the test; 65 scan, 170 scan, and 270 scan. Vapor extraction was performed at a constant 580 scan for the duration.

The combined sparging/ISV process removed a total of 16,000 lb of VOCs (TCE and PCE) from the soil and groundwater during a 140-day test. The rate of removal remained nearly constant for the duration of the test, ranging from approximately 175 lb/day during the first four days, to 120 lb/day at the test midpoint, and decreasing slightly to 100 lb/day during the final 3 weeks (days 120 to 140). Photographs A.3-2 and A.3-3 show a pictorial representation of the distribution of TCE in M-area soils before and after the air sparging test.

A.3.2.2 BIO-SPARGING

A follow-on test was conducted, using the above apparatus to test the feasibility of in-situ biodegradation by injecting gaseous-phase nutrients with the air sparging system. The system was operated at a 240 scfm vapor extraction rate and 200 scfm injection rate. Methane was mixed with the sparging air at ratios of 1% (20% of the lower explosive limit or LEL) and 4% (80% of the LEL) to provide a carbon source to stimulate biological activity. Test variations included adding nitrogen (as nitrous oxide) and phosphorous (triethyl phosphate), to further enhance biological activity, and pulsed injection cycles to optimize the utilization of nutrients and increase the quantity of contaminant broken down by in-situ degradation rather than removed by vapor extraction. The monitoring required to determine the fate of contaminants and nutrients and estimate the rate of degradation during the test is complex. The rate of degradation of TCE and PCE are indicated by measuring free chloride levels in groundwater. Biological activity is determined by measuring the relative levels of methane and carbon dioxide in the extracted soil gas and performing microbe population density counts in groundwater samples. TCE and PCE removal by vapor extraction is measured directly from extraction soil gas samples. The combined effect of biological degradation and vapor extraction is monitored by comparing TCE/PCE concentrations and free chloride concentrations in groundwater to soil gas VOC removal rates and estimating a net destruction/removal rate.

A.3.2.3 ISV AND THERMALLY ENHANCED ISV

Soil contamination has also been detected along the length of the industrial waste sewer which once served the Area-M Basins. Vadose zone soils contained up to 200 $\mu\text{g/g}$ TCE and 6 $\mu\text{g/g}$ PCE. The site stratigraphy is similar to that described above. Two attempts have been made to apply ISV to this area.

In the first attempt, Terravac installed five standard vertical extraction wells. A pilot test was performed using the five vertical wells using an extraction rate of 400 to 500 scfm. A total of 1,036 lb TCE and 460 lb PCE were removed during

the six-day test. A radius of influence of greater than 50 feet was measured for all five wells.

In the second trial, a single fiberglass horizontal well was installed along the alignment of the abandoned sewer line at a depth of approximately 40 feet bgs, with an approximate 550 foot total length and 350 foot slotted midsection. The extraction process was enhanced by the insertion of a 25 KW radio-frequency (RF) antenna into the extraction pipe to heat the soils immediately surrounding the pipe. The test procedure is outlined in Attachment 4, "Savannah River Site, In-Situ Radio Frequency Heating Demonstration, Field Test Plan." The test results are provided in "In-Situ Radio Frequency Soil Remediation Heating Demonstration, Westinghouse, 1993," a copy of which was not available at the time of the site visit. The following information was obtained from interviews with Westinghouse personnel. The test required 27 days to complete. Soils were heated to a temperature of at least 65°C for a radius of approximately 7 feet around the antenna. A discernable rise in soil temperature occurred for a radius of approximately 10 feet around the antenna. Westinghouse estimates that 190 KWH were required for each cubic yard of soil treated to boil off water and that another 60 KWH/CY is required to reach 65°C. A total of 2,000 CY of soil is estimated to have been treated. Because RF transmission is not dependent upon conduction by fluids, this technology is applicable to clays where permeability to air, steam, and electrolyte is poor.

A.3.2.4 OFFGAS TREATMENT

The air sparging and ISV systems at the demonstration site have successfully tested several technologies for offgas treatment to remove or destroy VOCS. These technologies included carbon adsorption, biological degradation in a soil chamber, catalytic oxidation with TiO_2 and UV light, and catalytic oxidation with electrically heated platinum/palladium. No data or publications were available at the time of the site visit concerning the efficiency, costs, or technical details of implementation for these technologies. Information on these tests is (or will be)

available in reports listed under SR 121107: Remediation on the attached publications list and has been requested from Westinghouse Savannah River Company.

A.3.3 CONCLUSIONS

The ISV, thermally-enhanced ISV, air sparging, and biosparging technologies have been very successful at the SRS Area-M Basins and adjacent industrial sewer lines sites. The net destruction/removal of VOCs from the basins' soils after the combined treated of air sparging and biosparging is reported to be 78%. No data was presented on the total effectiveness (i.e. residual soil concentrations or soil gas levels) of ISV and thermally-enhanced ISV at the industrial sewer line, but reported removal rates were encouraging. The integrated demonstration process has the advantage of comparing the short-term removal rates and costs per pound of contaminant for various technologies under nearly identical conditions. The disadvantage is that we can't easily compare the maximum net removal possible if each technology was operated to completion (and incremental cost each. technology might incur if operated for the length of time necessary to achieve various residual contaminant quantities which might be selected as defining successful completion).

A.3.4 RECOMMENDATIONS

The stratigraphy at AFP4 differs radically from that at SRS. SRS soils are largely composed of sands and silts interspersed with clay fingers and lenses. The soils at AFP4 consist of a 3 to 5 foot thick surface layer of granular material (possibly fill), underlain by a 15 foot thick layer of "terrace alluvial material ... composed of heterogeneous interbedded clay, silt, sand, and gravel" (Feasibility Study Report, page 1-19), and two limestone strata. The presence of perched groundwater (probably from leaking floor drains, sumps, and roof drains rather than naturally occurring) on the top of the terrace material indicates a low vertical permeability.

Air sparging alone has a low probability of success at AFP4, because the majority of contamination is present in and beneath the terrace deposits, which act as an aquitard. Intensive aeration would probably only build up air pockets in the limestone and drive groundwater away from the sparging well(s). The key to success is the ability to remove gases from the interface between the terrace deposits and the Goodland limestone at a rate equal to or greater than the sparging injection rate.

Biosparging is potentially applicable if the injection cycles are pulsed to prevent build-up of large air pockets. Extraction could be performed at the terrace deposit/limestone interface after an interval to allow efficient utilization of the carbon source and micronutrients. Bioremediation of the terrace deposits may be possible by injection of air and gaseous nutrients through horizontal wells. Establishment of flow patterns and adequate recovery of injected gases must be determined by tracer gas (helium or other) testing. If permeabilities are not adequate, flow can be enhanced by pneumatic fracturing.

Bioremediation using aqueous-phase nutrient supply is potentially applicable to the limestone strata, but probably not to the terrace deposit aquitard. Dye tracer studies or other means of determining nutrient distribution are needed to design a successful circulation system.

Thermally enhanced ISV is potentially applicable to the terrace deposits, provided perched groundwater can be isolated from the treatment zone and that shrinkage of the clays will not create subsidence and structural problems. The least intrusive technique may be install horizontal wells in the terrace deposits and use either injection of hot air in a push-pull arrangement or RF heating. Alternatively, air could be injected into the terrace deposits and extraction performed both above and below the formation.

FORT WORTH

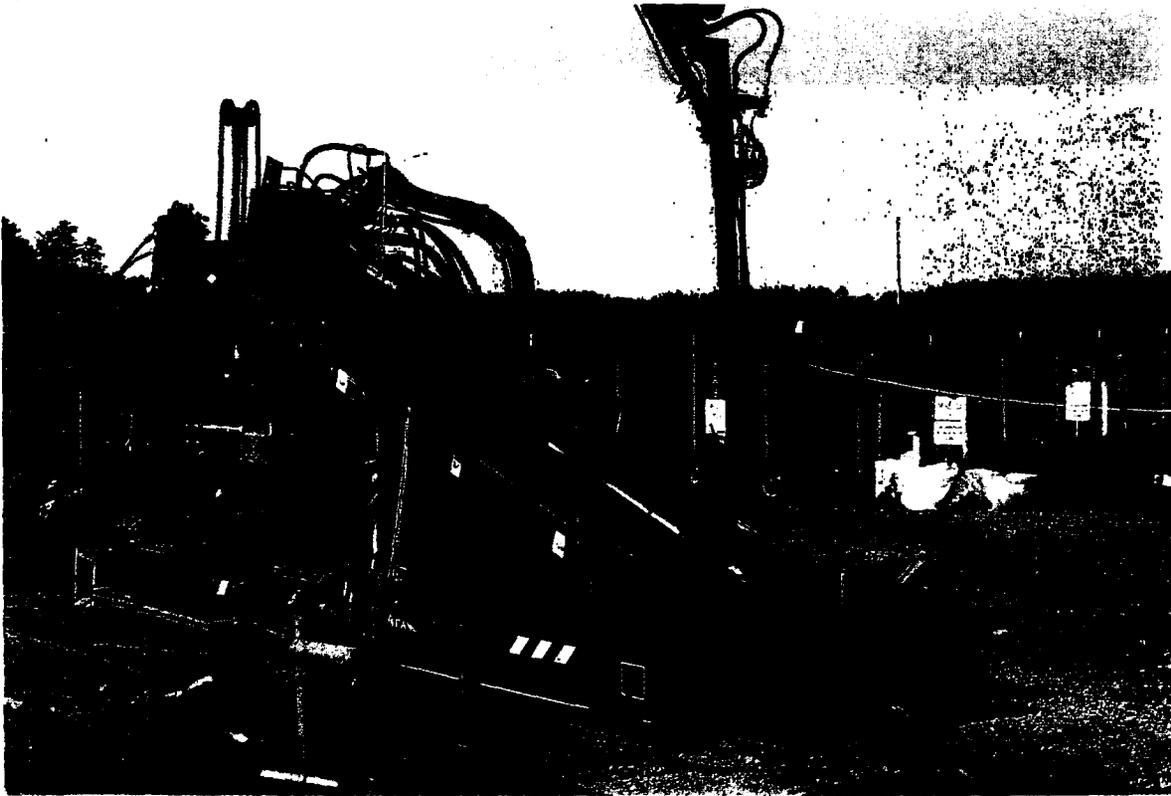


Figure A.3-1
MODIFIED MODEL X-810 HORIZONTAL BORING MACHINE, CHARLES MACHINE WORKS/DITCH WITCH
SOURCE: U.S. DEPARTMENT OF ENERGY, 1993.

| COLOR

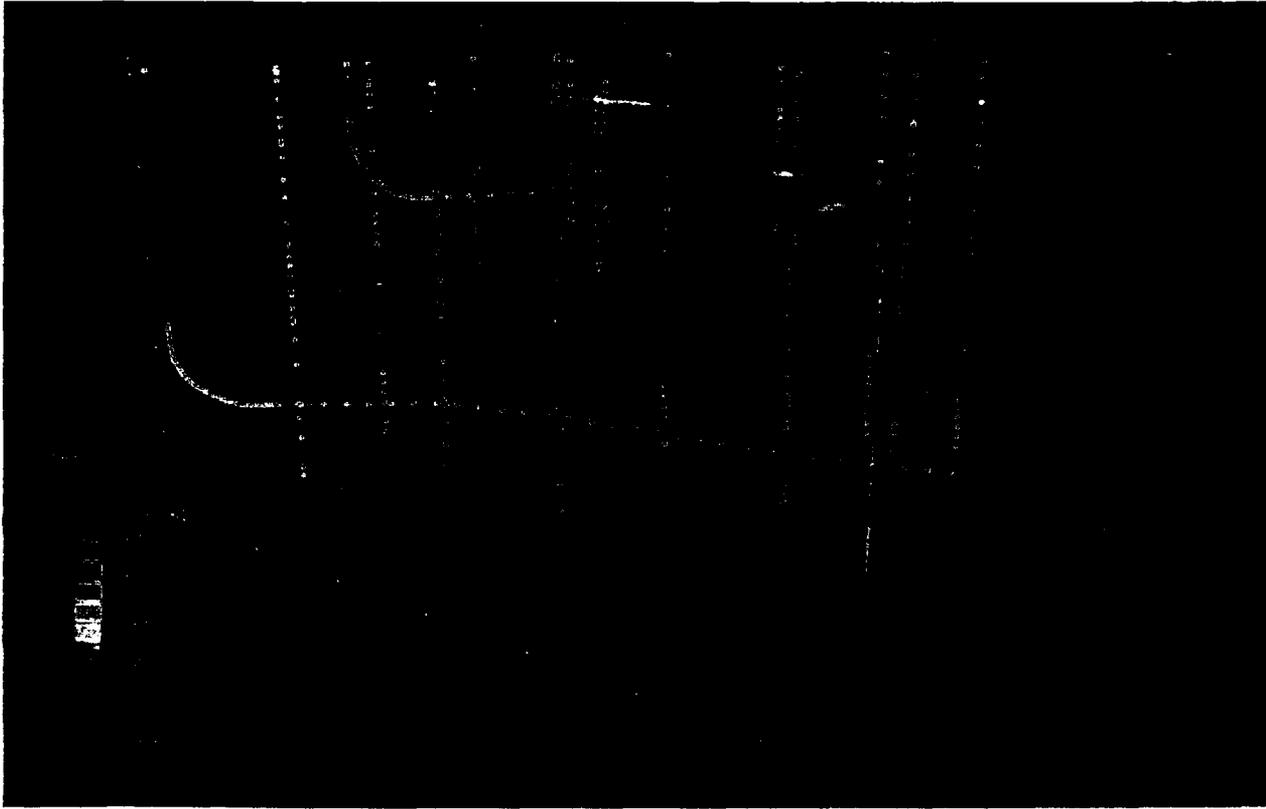


Figure A.3-2
TRICHLOROETHENE DISTRIBUTION IN AREA M SOILS PRIOR TO RATION
SOURCE: U.S. DEPARTMENT OF ENERGY, 1993.



Figure A.3-3
TRICHLOROETHENE DISTRIBUTION IN AREA M SOILS AT CONCLUSION OF AIR SPARGING TEST
SOURCE: U.S. DEPARTMENT OF ENERGY, 1993.

COLOR

AL 121101: Analysis and Evaluation

- (0) Bentley, H., and B. I. Travis. 1991. "Modeling In-Situ Biodegradation in Unsaturated and Saturated Soils." Proceedings of US-EPA Symposium on Soil Venting, Houston, TX
- (3) Brookshire, D. S. and M. McKee. 1992. "A Conceptual Framework for Conducting Cost-Effectiveness Analysis of Competing Groundwater Contamination Remediation Strategies." (Report submitted to Linda Trocki, AET, LANL). LA-UR 92-3633, 9/1992. I strategies, (Report submitted to Linda Trocki, AET, LANL).
- (0) Hamming, R. W. 1973. Numerical Methods for Scientists and Engineers, 2nd Edition, McGraw-Hill, New York, NY.
- (3) Henricksen, A. D. and S. R. Booth. 1992. "Cost Effectiveness of an Innovative Technology for VOC Detection: The Direct Sampling Ion Trap Mass Spectrometer." Report LA-UR-92-3527.
- (0) Rosenberg, N. D., B. J. Travis, J. D. Schroeder, B. B. Looney, C. A. Eddy, S. R. Booth, D. S. Brookshire and M. McKee. "Environmental Restoration Technology Demonstrations at DOE's Savannah River Site." To be presented at the American Geophysical Union fall meeting, San Francisco, CA (abstract published in EOS Transactions 73, p.225).
- (8) Schroeder, J. D., N. D. Rosenberg, E. P. Barnes-Smith, and S. R. Booth. 1992. "In-Situ Air Stripping: Cost Effectiveness of Remediation Technology Field Tested at the Savannah River Integrated Demonstration Site." Los Alamos National Laboratory Report, LA-UR-92-1927. 6/1992.
- (0) Schroeder, J. D., S. R. Booth and L. K. Trocki. "Cost Effectiveness of the Site Characterization and Analysis Penetrometer System." Report LA-UR-91-4016. 12/1991.
- (1) Schroeder, J. D., S. R. Booth, L. K. Trocki, A. G. Turpin, R. B. Kidman and J. H. Pendergrass. "Cost Savings From Integration of a Demonstration Program: The Savannah River Integrated Demonstration Project (SRIDP)." Report LA-UR-91-1485.
- (0) Travis, B. J. and E. Nuttall. 1987. "Two-Dimensional Numerical Simulation of Geochemical Transport in Yucca Mountain." LA-10532-MS.
- (0) Travis, B. J. and B. C. Trent. 1991. "Three Dimensional Computer Simulations of Bioremediation and Vapor Extraction." Proceedings of Environmental Remediation Conference, ER '91, Pasco, WA, LA-UR-91-2875.
- (0) Travis, B. J. and K. Birdsell. 1990. "TRACR3D: A Model of Flow and Transport in Porous Media: Model Description and User's Manual." LA-11798-M.
- (1) Travis, B. J., N. D. Rosenberg and K. H. Birdsell. 1993. "Numerical Simulations of In Situ Bioremediation at the Savannah River Site."

AL 201101: Monitoring and Characterization

- (5) (all in folder) Ballard, S. 1992. "In Situ Permeable Flow Sensors at the Savannah River Integrated Demonstration: Phase I Results." SAND92-1952, Sandia National Laboratories, Albuquerque, New Mexico.

- (0) Ballard, S. 1992. "Monitoring Groundwater Flow Around an Air-Stripping Waste Remediation Experiment at the Savannah River Site, SC." AGU 1992 Fall Meeting Program and Abstracts, p. 165.
- (5) (all in folder) Ballard, S. 1992 "An In Situ Permeable Sensor to Monitor Groundwater Flow." Sensors, 9(13): 20.
- (0) Ballard, S., M. Thompson, L. Romero. 1991. "A New Device for the In-Situ Measurement of Groundwater Flow Velocity." AGU 1991 Fall Meeting Program with Abstracts, p. 216.
- (1) Elbring, G. J. 1993. "Crosswell Seismic Imaging of an In-Situ Air Stripping Waste Remediation Process." Proceedings of the Symposium on Application of Geophysics to Engineering and Environmental Problems. 1: 55-63.
- (1) Elbring, G. J. 1992. "Crosshole Shear-Wave Seismic Monitoring of an Air Stripping Waste Remediation Process." SAND91-2742, Sandia National Laboratories, Albuquerque, New Mexico.
- (0) Elbring, G. J. 1991. "Using Crosswell Seismic Imaging to Monitor In-Situ Air Stripping Waste Remediation Processes." AGU 1991 Fall Meeting Program and Abstracts, p. 295.

OR 111101: Bioremediation

- (0) Bowman, J., L. Jimenez, I. Rosario, and G. S. Saylor. "Methanotrophic Bacteria from Contaminated Subsurface Sites: Characterization, Soluble Methane Monooxygenase Activity, Gene Probe Analysis, and TCE Degradation Studies." (In preparation)
- (5) (all in folder) Bowman, J., L. Jimenez, I. Rosario, T. C. Hazen, and G. S. Saylor. 1993. "Characterization of Methanotrophic Bacterial Communities Present in a Trichloroethylene Contaminated Subsurface Groundwater Site." Appl. Environ. Microbiol. 59(8).
- (0) Bratina, B. J., G. A. Brusseau and R. S. Hanson. 1992. " Use of 16S rRNA Analysis to Investigate the Phylogeny of Methylo-trophic Bacteria." Int. J. Systematic Bacteriol. 42: 645-648.
- (0) Brusseau, G. A., E. S. Bulygina and R. S. Hanson. 1993. "Phylogenetic Analysis and Development of Probes for Differentiating Methylo-trophic Bacteria." Appl. Environ. Microbiol. (Submitted).
- (1) Hanson, R. S., B. J. Bratina and G. A. Brusseau. 1992. "Phylogeny and Ecology of Methylo-trophic Bacteria." Microbial Growth on One-Carbon Compounds (J. C. Murrell and D. P. Kelley editors) Andover Press. Hampshire, U. K. pp. 285-302.
- (0) Jimenez, L., I. Rosario, C. Werner, S. Koh, R. Hanson, T. C. Hazen, and G. S. Saylor. "Molecular Environmental Diagnostics of Contaminated Subsurface Environments." Manuscript in review by Westinghouse Savannah River Co.
- (1) Jimenez, L., I. Rosario, J. Bowman, S. Koh, and G. S. Saylor. 1993. "Molecular Environmental Diagnostics of TCE Contaminated Subsurface Environments." In Situ and On-Site Bioreclamation, The Second International Symposium, San Diego, CA.

- (0) Jimenez, L., I. Rosario, C. Werner, S. Koh, and G. S. Sayler. "Molecular Environmental Diagnostics of Contaminated Subsurface Sites." 92nd Annual Meeting of the American Society for Microbiology, May 1992, New Orleans, LA.
- (0) Koh, S., J. P. Bowman, and G. Sayler. 1993. "Soluble Methane Monooxygenase Production and Trichloroethylene Degradation by a Type I Methanotroph, *Methylomonas methanica* 68-1." Appl. Environ. Microbiol. 59: 960-967.
- (6) (all in folder) Koh, S., I. Rosario, C. Werner, A. Heitzer, L. Jimenez, and G. S. Sayler. "Comparative Molecular Analysis of Deep Subsurface Environments." [abs] 91st Annual Meeting of the American Society for Microbiology, May 1991, Dallas, TX.
- (6) (all in folder + 5 abs) Korde, V. M., T. J. Phelps, P. R. Bienkowski, and D. C. White. 1993. "Biodegradation of Chlorinated Aliphatics and Aromatic Compounds in Total-Recycle Expanded-Bed Biofilm Reactors." Applied Biochemistry and Biotechnology. 39/40: 631-641.
- (0) Korde, V. M., T. J. Phelps, P. R. Bienkowski, and D. C. White. 1992. "Biodegradation of Chlorinated Aliphatics and Aromatic Compounds in a Recycle Expanded-Bed Bioreactor." 14th Symposium on Biotechnology of Fuels and Chemicals, Gatlinburg, TN.
- (5) (all in folder) Lackey, L. W., T. J. Phelps, S. Nold, D. Ringelberg, V. Korde, P. R. Bienkowski and D. C. White. "Feasibility Testing for the On-Site Bioremediation of Organic Wastes by Native Microbial Consortia." (Manuscript in press) [abs].
- (6) (all in folder + 5 abs) Lackey, L. W., T. J. Phelps, P. R. Bienkowski, and D. C. White. 1993. "Biodegradation of Chlorinated Aliphatic Hydrocarbon Mixtures in a Single-Pass Packed-Bed Reactor." Applied Biochemistry and Biotechnology. 39/40: 701-713.
- (1) Lackey, L. W., O. F. Webb, T. J. Phelps, P. R. Bienkowski, and D. C. White. 1992. "Utilization of Differential Volume Reactor Systems for Fate Analysis of Trichloroethylene in Subsurface Environments." (Manuscript submitted)
- (5) (all in folder) Malachowsky, K., T. J. Phelps, A. B. Teboli, D. E. Minnikin, and D. C. White. "Aerobic Mineralization of Trichloroethylene, Vinyl Chloride, and Aromatic Compounds by *Rhodococcus* Species." [abs] (paper in press).
- (5) (all in folder) Malachowsky, K., T. J. Phelps, and D. C. White. 1992. "Aerobic Degradation of Trichloroethylene (TCE) Vinyl Chloride (VC) and Aromatic Compounds by Type IV Actinomycetes." American Society for Microbiology, 92nd General meeting, New Orleans, LA.
- (0) Malachowsky, K., T. J. Phelps, and D. C. White. 1991. "Aerobic Mineralization of Vinyl Chloride by Branched-Shaped Gram-Positive Bacteria." in Abstracts of the Annual Meeting of the American Society for Microbiology.
- (10) (all in folder + 5 abs) Morrissey, C. M., S. E. Herbes, A. V. Palumbo, T. J. Phelps, and T. C. Hazen. 1993. "Use of Laboratory Soil Columns to Optimize In-Situ Biotransformation of Tetrachloroethylene." In Situ and On-Site Bioreclamation: The Second International Symposium, San Diego, CA. (paper in press).
- (1) Niedzielski, J. J., R. M. Schram, T. J. Phelps, S. E. Herbes, and D. C. White. 1989. "A Total-Recycle Expanded-Bed Bioreactor Design which Allows Direct Headspace Sampling of Volatile Chlorinated Aliphatic Compounds." J. Microbiol. Methods. p. 1-7.

- (5) (all in folder) Nold, S., L. Lackey, D. Ringelberg, and D. White. 1992. "Changes in Community Structure and Physiological Status of a Bacterial Consortia During Degradation of Trichloroethylene (TCE)." [abs] American Society for Microbiology, 92nd General Meeting, New Orleans, LA.
- (0) Palumbo, A. V., T. J. Phelps, C. M. Morrissey, S. E. Herbes, G. Sayler, and L. Jiminez. "Monitoring Microbial Activity and Biomass During the Methane Injection Campaign." In *Situ and On-Site Bioreclamation, Second International Symposium, San Diego, California.* (In preparation)
- (5) (all in folder) Palumbo, A. V., T. J. Phelps, G. S. Sayler, D. C. White, and S. M. Pfiffner. "Integrated Demonstration of TCE Degradation: Biological Monitoring of Critical Populations." [abs].
- (5) (all in folder + 5 abs) Palumbo, A. V., P. A. Boerman, S. E. Herbes, G. W. Strandberg, T. L. Donaldson, A. J. Lucero, H. L. Jennings, T. J. Phelps, and D. C. White. 1991. "A Co-Metabolic Approach to Groundwater Remediation." *Environmental Remediation 1991: Cleaning Up the Environment for the 21st Century.* pp. 95-99.
- (5) (all in folder) Pfiffner, S. M., R. Mackowski, D. C. White, and T. J. Phelps. 1993. "Monitoring of Microbial Populations and Activities from Groundwater for In-Situ Trichloroethylene Remediation." [abs] American Society for Microbiology, 93rd General Meeting, Atlanta, GA.
- (11) (all in folder) Phelps, T. J., S. M. Pfiffner, R. Mackowski, D. Ringelberg, and D. C. White. 1993. "Application of Microbial Biomass and Activity Measures to Assess In-Situ Bioremediation of Chlorinated Solvents." [abs] *In Situ and On-Site Bioreclamation: The Second International Symposium, San Diego, CA.* (paper in press).
- (12) (all in folder + 5 abs) Phelps, T. J., J. J. Niedzielski, K. Malachowsky, R. M. Schram, S. E. Herbes, and D. C. White. 1991. "Biodegradation of Mixed-Organic Wastes by a Microbial Consortia in Continuous-Recycle Expanded-Bed Bioreactors." *Environ. Sci. & Technol.* 25: 1461-1465.
- (11) (all in folder + 5 abs) Phelps, T. J., K. Malachowsky, R. M. Schram, and D. C. White. 1991. "Aerobic Mineralization of Vinyl Chloride by a Bacterium of the Order *Actinomycetales*." *Appl. Environ. Microbiol.* 57(4): 1252-1254.
- (5) (all in folder + 5 abs) Phelps, T. J., J. Niedzielski, and D. C. White. 1991. "Biodegradation of Mixed Organic Wastes by Microbial Consortia Enriched from Subsurface Sediments." in *Proceedings of the First International Symposium on Microbiology of the Deep Subsurface.* (C. B. Fliermans and T. C. Hazen editors), WSRC Information Services, Aiken, SC. pp. 7-71-80.
- (11) (all in folder + 5 abs) Phelps, T. J., J. J. Niedzielski, R. M. Schram, S. E. Herbes, and D. C. White. 1990. "Biodegradation of Trichloroethylene in Continuous-Recycle Expanded-Bed Bioreactors." *Appl. Environ. Microbiol.* 56: 1702-1709.
- (0) Phelps, T. J., D. B. Ringelberg, J. B. Guckert, and D. C. White. 1990. "Biochemical Markers for In Situ Microbial Community Structure of Subsurface Sediments." Abstracts of the American Geophysical Union.

- (1) Phelps, T. J., L. Lackey, V. Korde, J. J. Niedzielski, and D. C. White. 1990. "Bioremediation of Mixed Organic Wastes by Microbial Consortia Enriched from Sub-surface Sediments." Abstracts of the American Institute of Corrosion Engineers, Summer Meeting.
- (0) Sayler, G. S. 1992. "Molecular Approaches for Diagnostics, Performance Monitoring and Optimization in Bioremediation." U. S. Environmental Protection Agency, Tel Aviv, Israel.
- (0) Sayler, G. S. 1992. "Environmental Biotechnology's Future in Hazardous Waste Management." Third Pacific Rim Biotechnology Conference, Taipei, Taiwan.

OR 121104: Monitoring and Characterization

- (0) Kearl, P. M., N. E. Korte, and T. A. Cronk. 1992. "Suggested Modifications to Groundwater Sampling Procedures Based on Observations Using the Colloidal Borescope." Groundwater Monitoring Review, Spring: 155-161.

RL 331003: Remediation

- (5) (all in folder) Bergsman, T. M., J. S. Roberts, D. L. Lessor, and W. O. Heath. 1993. "Six Phase Soil Heating to Enhance Removal of Contaminants." PNL-SA-21709, Pacific Northwest Laboratory, Richland, WA 99352.
- (5) (all in folder) Bergsman, T. M., J. S. Roberts, D. L. Lessor, and W. O. Heath. 1993. "Field Test of Six Phase Heating and Evaluation of Engineering Design Code." PNL-SA-21537, Pacific Northwest Laboratory, Richland, WA 99352.
- (0) Heath, W. O., S. C. Goheen, M. C. Miller, R. L. Richardson. 1992. "Investigation of Electrical Fields for Low-Temperature Treatment of Soils and Liquids." Presented at A&WMA and EPA's International Conference In Situ Treatment of Contaminated Soil and Water, Cincinnati, Ohio.
- (5) (all in folder) Heath, W. O., J. S. Roberts, D. L. Lessor, and T. M. Bergsman. 1992. "Engineering Scaleup of Electrical Soil Heating of Soil Decontamination." Presentation at Spectrum '92, Boise, Idaho.

RL321101: Off-Gas Corona

- (5) (all in folder) Virden, J. W., W. O. Heath, S. C. Goheen, M. C. Miller, G. M. Mong, and R. L. Richardson. 1992. "High-Energy Corona for Destruction of Volatile Organic Contaminants in Process Off-Gas." PNL-SA-20741, Pacific Northwest Laboratory, Richland WA 99352.

RL321102: Bioremediation

- (5) (all in folder) Brockman, F. J., W. Sun, A. Ogram, W. Payne, and D. Workman. 1993. "Baseline Characterization and Remediation-Induced Changes in TCE Degradative Potential Using Enrichment Techniques and DNA Probe Analysis." in press, In Situ Bioremediation.

- (5) (all in folder) Brockman, F. J., D. Workman, W. Sun, and A. Ogram. 1993. "Baseline Characterization of TCE Degradative Potential by Enrichment Techniques and DNA Probe Analysis." Abstracts of the Second International Symposium on In Situ and On Site Bioreclamation.
- (5) (all in folder) Sun, W., A. Ogram, W. Payne, and F. J. Brockman. 1993. "Assessment of TCE Degradative Potential in a Contaminated Aquifer by Gene Probe Analysis." Abstracts of the 93rd General Meeting of the American Society for Microbiology. p. 378.

SF 221102: Monitoring and Characterization

- (0) Ramirez, A. L., W. D. Daily, and D. LaBrecque. 1992. "Electrical Resistance Tomography Used in Environmental Restoration." Lawrence Livermore National Lab, UCRL-JC-110356, Livermore, CA, Proceedings of the Information Exchange Meeting on Characterization, Sensors, and Monitoring Technologies, Dallas, TX, sponsored by US DOE.
- (2) (all in folder) Ramirez, A. L., W. D. Daily, E. Owen, D. LaBrecque. 1991. "Using High Frequency Electromagnetic and Electrical Resistance Tomography to Determine the Effectiveness of a Remediation Process." Lawrence Livermore National Laboratory, UCRL-JC-107780, Livermore, CA.

SR 121101: Directional Drilling

- (5) "Demonstration of a Utility Industry Horizontal Drilling System: Horizontal Well AMH-5 Installation Report." 1993. WSRC-TR-93-008.
- (5) "Demonstration of River Crossing Technology for Installation of Environmental Horizontal Wells: AMH-6 and AMH-7 Installation Report." 1993. WSRC-TR-93-387.
- (5) "Demonstration of Eastman Christensen Horizontal Drilling System Integrated Demonstration Site Savannah River Site." 1992. WSRC-TR-92-577.
- (5) (all in folder) Kaback, D. S., B. B. Looney, C. A. Eddy, and T. C. Hazen. 1992. "Innovative Ground Water and Soil Remediation Using Horizontal Wells." Innovative Technologies for Cleaning the Environment, Erice, Italy.
- (5) (all in folder) Kaback, D. S., B. B. Looney, C. A. Eddy, and T. C. Hazen. 1991. "Innovative Ground Water and Soil Remediation: In Situ Air Stripping Using Horizontal Wells." National Water Well Association Fifth Outdoor Action Conference Proceedings, Las Vegas, NV.
- (10) (all in folder) Kaback, D. S., B. B. Looney, J. C. Corey, L. M. Wright, and J. L. Steele. 1989. "Horizontal Wells for In Situ Remediation of Groundwater and Soils." National Water Well Association Third Outdoor Action Conference Proceedings, Orlando, FL.
- (5) Kaback, D. S., B. B. Looney, J. C. Corey, and L. M. Wright. 1989. "Well Completion Report on Installation of Horizontal Wells for In Situ Remediation Tests." WSRC-RP-89-784.

- (14) (all in folder) Looney, B. B., D. S. Kaback, and J. C. Corey. 1991/1992. "Field Demonstration of Environmental Restoration Using Horizontal Wells." Third Forum on Innovative Hazardous Waste Treatment Technologies: Domestic and International, Dallas TX (EPA); Waste Management '91 Conference (DOE), Tucson AZ; Live Satellite Seminar sponsored by Air and Waste Management Association.
- (5) (all in folder) "The Summary of National Environmental Needs." 1993. WSRC-TR-93-388.
- (0) "Summary Report of the Drilling Technologies Tested at the Integrated Demonstration Site." 1993.
- (0) Wilson, D. D. and D. S. Kaback. 1993. "Industry Survey for Horizontal Wells Final Report." WSRC-TR-93-511.

TTP121102: Characterization and Monitoring

- (1) Cernosek, R. W., G. C. Frye and D. W. Gilbert. 1993. "Portable Acoustic Wave Sensor Systems for Real-Time Monitoring of Volatile Organic Compounds." Proc. ISE.
- (0) Colston, Jr., B. W., S. B. Brown, P. F. Daley, K. Langry, F. P. Milanovich. 1992. "Monitoring Remediation of Trichloroethylene Using a Chemical Fiber Optic Sensor: Field Studies." in Proceedings of the International Topical Meeting on Nuclear and Hazardous Waste Management. 1: 393-396.
- (5) (all in folder) Eckenrode, B. A., B. Owens, and J. Rossabi. 1992. "On Site Well Screening with a Transportable GC/MS System." Environmental Lab 4(1): 42 .
- (5) (all in folder) Eddy, C. A. and B. B. Looney. 1993. "Three Dimensional Digital Imaging of Environmental Data: Selection of Gridding Parameters." International Journal of Geographic Information Systems 7(2): 161-172.
- (0) Eddy, C. A. and B. B. Looney. 1992. "Three-Dimensional Imaging of Environmental Data: Optimal Selection of Gridding Parameters for Volumetric Calculations." [abs]: EOS Transactions of the American Geophysical Union. 73(43): 230.
- (5) (all in folder) Eddy, C. A., B. B. Looney, and D. S. Kaback. 1992. "Comparison of Innovative Depth Discrete Sampling Technologies for Sediments and Groundwater for Environmental Characterization." Proceedings of the 1992 Waste Management and Environmental Sciences Conference, Puerto Rico, p. 124-133.
- (6) Eddy, C. A., B. B. Looney, J. M. Dougherty, T. C. Hazen, and D. S. Kaback. 1991. "Characterization of the Geology, Geochemistry, Hydrology and Microbiology of the In-situ Air Stripping Demonstration Site at the Savannah River Site." Westinghouse Savannah River Company, WSRC-RD-91-21.
- ***Kaback, D. S., B. B. Looney, J. C. Corey, L. M. Wright, and J. L. Steele. 1989. "Horizontal Wells for In-Situ Remediation of Groundwater and Soils." in Proceedings of the Third National Outdoor Action Conference on Aquifer Restoration, Groundwater Monitoring and Geophysical Methods, Association of Ground Water Scientists and Engineers, Orlando, FL. pp. 121-135.

- (0) Looney, B. B., C. A. Eddy, and W. R. Sims. "Evaluation of a Rapid Headspace Analysis Method for Analysis of Volatile Constituents in Soils and Sediments." Groundwater Monitoring Review. (in revision).
- (5) (all in folder) Looney, B. B., C. A. Eddy, and W. R. Sims. 1993. "Evaluation of Headspace Method for Volatile Constituents in Soils and Sediments." Proceedings of the National Symposium on Measuring and Interpreting VOC's in Soils: State of the Art and Research Needs, Las Vegas, Nevada. 8 p.
- (5) Looney, B. B., J. Rossabi, D. M. Tuck, C. L. Bergren, R. Van Pelt, W. E. Jones, A. E. Stevenson, and B. S. Kristiansen. 1992. "Assessing DNAPL Contamination, A/M Area, Savannah River Site: Phase I Results (U)." WSRC-RP-1302. Westinghouse Savannah River Company, Aiken, SC. pp. 1-85.
- (5) Looney, B. B., T. C. Hazen, D. S. Kaback, and C. A. Eddy. 1991. "Full Scale Field Test of the In Situ Air Stripping Process at the Savannah River Integrated Demonstration Test Site (U)." WSRC-RD-91-22. Westinghouse Savannah River Company, Aiken, SC. pp. 1-18.
- (1) Lowry, W. E. and S. D. Dunn. 1993. "Seamist Depth Discrete Sampling and Monitoring of the Vadose Zone at the Savannah River Site." SEASF-FR-93-005.
- (0) Milanovich, F. P., P. F. Daley, K. Langry, B. W. Colston, S. B. Brown, and S. M. Angel. 1991. "A Fiber Optic Sensor for Continuous Monitoring of Chlorinated Hydrocarbons." in Proceedings of the Second International Symposium on Field Screening Methods for Hazardous Wastes and Toxic Chemicals. EPA/600/9-91/028. EPA, Las Vegas. pp. 43-48.
- (7) (all in folder) Nichols, R. L., B. B. Looney, and J. E. Heddleston. 1992. "Three Dimensional Digital Imaging." Environmental Science and Technology, 26(4): 642-649.
- (5) (all in folder) Rossabi, J. "The Savannah River Technology Center Environmental Monitoring Field Test Platform." Proceedings of the Third International Symposium-Field Screening Methods for Hazardous Waste and Toxic Chemicals, Las Vegas, Nevada. (in press).
- (5) (all in folder) Rossabi, J. "In-Situ, Subsurface Monitoring of Vapor Phase TCE Using Fiber Optics." Proceedings of the Third International Symposium-Field Screening Methods for Hazardous Waste and Toxic Chemicals, Las Vegas, Nevada. (in press).
- (5) (all in folder) Rossabi, J., B. B. Looney, B. Riha, A. Ferrilli, and N. Smith. 1992. "The Influence of Surface Pressure Fluctuation on Surface/Subsurface Air Migration." [abs]: EOS Transactions of the American Geophysical Union. 73(43): 233.
- (5) Rossabi, J. 1992. "Fiber Optic Sensors for Environmental Application: A Brief Review." Westinghouse Savannah River Company, WSRC-RP-92-471.
- (0) Rossabi, J., B. A. Eckenrode, and B. Owens. 1992. "Onsite Well Screening with a Transportable Gas Chromatography/Mass Spectrometer System." Westinghouse Savannah River Company, WSRC-RP-91-603.
- (0) Sims, W. R., B. B. Looney, and C. A. Eddy. 1991. "Evaluation of a Rapid Headspace Analysis Method for Analysis of Volatile Constituents in Soils and Sediments." Proceedings of the Fifth National Outdoor Action Conference on Aquifer Restoration, Ground Water Monitoring, and Geophysical Methods.

SR 121106: Bioremediation

- (5) (all in folder) Andrews, G. F., S. G. Hansen, and W. C. Downs. 1993. "The Rate of TCE Degradation by Indigenous Methanotrophic Bacteria at the Savannah River Site." [abs] Invited Seminar Speaker, *In Situ and On-Site Bioreclamation*, The Second International Symposium, San Diego, CA. (paper in press).
- (5) (all in folder) Berry*, C. J., T. C. Hazen, M. M. Franck and J. Rossabi. 1993. "Methanotrophic Treatment of Contaminated Well Water Using a Pilot Scale Bioreactor." [abs] *In Situ and On-Site Bioreclamation*, The Second International Symposium, San Diego, CA. (paper in press).
- (5) (all in folder) Berry, C. J., M. M. Franck, K. Lombard, and C. B. Fliermans. "Degradation of Polycyclic Aromatic Hydrocarbons in Discarded Railroad Crossties." [abs].
- (5) (all in folder) Borthen, J., F. Meyer, K. Lombard, and T. Hazen. "Catalytic Oxidation of Trichloroethylene and Perchloroethylene Mixtures." AICHE 1993 Summer National Meeting, Control and Measurement of VOC Emissions.
- (5) (all in folder) Dougherty*, J. M., C. J. Berry, M. M. Franck, and T. C. Hazen. 1993. "Characterization of the Subsurface Microbial Community from a Trichloroethylene Contaminated Site." [abs] *In Situ and On-Site Bioreclamation*, The Second International Symposium, San Diego, CA. (paper in press).
- (0) Dougherty*, J. M., M. M. Franck, C. B. Fliermans, and T. C. Hazen. 1992. "Characterization of the Subsurface Microbial Community from a Trichloroethylene Contaminated Site." American Society for Microbiology Annual Meeting, New Orleans, LA.
- (0) Edwards*, N. T., B. T. Walton, T. A. Anderson, J. A. Beauchamp, L. W. Cooper, R. J. Luxmoore, E. G. O'Neill, G. S. Sayler, D. C. White, and T. C. Hazen. 1993. "The Use of Vegetation for Bioremediation of Surface Soils Contaminated with Trichloroethylene." [abs] *In Situ and On-Site Bioreclamation*, The Second International Symposium, San Diego, CA. (paper in press).
- (6) (all in folder) Enzien*, M. V., F. W. Picardal, T. C. Hazen, and R. G. Arnold. 1993. "Biodegradation of Trichloroethylene and Tetrachloroethylene under Aerobic Conditions with Methane Addition in a Sediment Column." [abs] *In Situ and On-Site Bioreclamation*, The Second International Symposium, San Diego, CA. (paper in press).
- (5) (all in folder) Enzien, M. V., F. Picardal, T. C. Hazen, R. G. Arnold, and C. B. Fliermans. 1993. "Reductive Dechlorination of Trichloroethylene and Tetrachloroethylene Under Aerobic Conditions in a Sediment Column." [abs].
- (6) (all in folder) Enzien*, M., F. Picardal, T. C. Hazen, and B. Arnold. 1992. "Effects of Trichloroethylene, Tetrachloroethylene, and Methane Exposure on Microbial Community Dynamics in a Sediment Column." [abs] American Society for Microbiology Annual Meeting, New Orleans, LA.

- (5) (all in folder) Fliermans*, C. B., J. M. Dougherty, M. M. Franck, P. C. McKinley and T. C. Hazen. 1993. "Immunological Techniques as Tools to Characterize the Subsurface Microbial Community at a Trichloroethylene Contaminated Site." [abs] Invited Seminar Speaker, **In Situ** and On-Site Bioreclamation, The Second International Symposium, San Diego, CA. (paper in press).
- (0) Hazen, T. C. 1993. "In Situ Bioremediation of Groundwater." Invited Seminar Chairman and Speaker, American Society for Microbiology Conference on Water Quality in the Western Hemisphere, San Juan, Puerto Rico.
- (0) Hazen*, T. C., J. M. Dougherty, and C. B. Fliermans. 1993. "DOE/SRS Integrated Demonstration: **In Situ** Bioremediation of Soil and Groundwater at a Chlorinated Solvent Contaminated Site using Horizontal Wells to Inject Air and Methane." [abs] Invited Seminar Speaker, **In Situ** and On-Site Bioreclamation, The Second International Symposium, San Diego, CA. (paper in press).
- (5) (all in folder) Hazen*, T. C., J. M. Dougherty, C. B. Fliermans, and B. B. Looney. 1993. "Bioremediation of Soil and Groundwater at a Chlorinated Solvent Contaminated Site using Horizontal Wells to Inject Air." [abs] Invited Seminar Speaker, **In Situ** and On-Site Bioreclamation, The Second International Symposium, San Diego, CA. (paper in press).
- (5) (all in folder) Hazen, T. C., B. B. Looney, M. Enzien, M. M. Franck, C. B. Fliermans, and C. A. Eddy. 1993. "In Situ Bioremediation via Horizontal Wells." I & EC Special Symposium, American Chemical Society, Atlanta, GA.
- (0) Hazen, T. C. 1992. "Emerging Technologies in Bioremediation." Workshop Chairman, American Society for Microbiology Training Workshop, New Orleans, LA.
- (0) Hazen, T. C. 1992. "In Situ Bioremediation Demonstrations at SRS." Invited Symposium Speaker, American Society for Microbiology Annual Meeting, New Orleans, LA.
- (0) Hazen*, T. C., J. M. Dougherty, and B. B. Looney. 1992. "Stimulation of Ground Water and Sediment Communities at a Trichloroethylene Contaminated Site." American Society for Microbiology Annual Meeting, New Orleans, LA.
- (5) (all in folder) Hazen*, T. C., J. M. Dougherty, C. B. Fliermans, and B. B. Looney. 1992. "Full Scale Underground Injection of Air, Methane, and Other Gases via Horizontal Wells for In Situ Bioremediation of Chlorinated Solvent Contaminated Ground Water and Soil." [abs] Invited Symposium Speaker, American Institute of Chemical Engineers annual meeting, Minneapolis, MN.
- (0) Hazen, T. C. 1992. "SRS Bioremediation Technology Licensing Symposium." SRS Technology Transfer Symposium, Augusta, GA.
- (0) Hazen, T. C. 1992. "In Situ Bioremediation Demonstrations at SRS." Invited Symposium Speaker, International Symposium on the Implementation of Biotechnology in Industrial Waste Treatment and Bioremediation, Grand Rapids, MI. Sponsored by Michigan Biotechnical Institute.
- (0) Hazen, T. C. 1992. "Monitoring **In Situ** Bioremediation." Invited Symposium Speaker, International Symposium on In Situ Bioremediation '92, Niagara-on-the-Lake, Canada. Sponsored by Environment Canada.

- (5) (all in folder) Hazen*, T. C., J. M. Dougherty, M. Enzien, M. M. Franck, C. B. Fliermans, C. A. Eddy, and K. H. Lombard. 1992. "DOE/SRS Integrated Demonstration: In Situ Bioremediation of Soil and Groundwater." [abs] DOE Technology Information Exchange: Remediation, Pleasanton, CA.
- (5) (all in folder) Hazen, T. C., K. Lombard, and C. B. Fliermans. "Full-Scale Prepared Bed Bioremediation Facility for Petroleum-Contaminated Soil." [abs] Invited Seminar. SRS-DOE Supplier Information Exchange Forum, Augusta, GA.
- (5) Hazen, T. C. 1991. "Test Plan for In Situ Bioremediation Demonstration of the Savannah River Integrated Demonstration Project DOE/OTD TTP No.: SR 0566-01 (U)." WSRC-RD-91-23. Westinghouse Savannah River Company, Aiken, SC.
- (0) Hazen, T. C. 1991. "Bioremediation/Biotechnology." Invited Keynote Speaker, Puerto Rico Conference on Advanced Technology/ InterAmerican University, San Juan, Puerto Rico.
- (0) Hazen, T. C. 1991. "Bioremediation at SRS." Invited Speaker, Annual Meeting of the Southeastern Society for Microbiology, Atlanta, GA.
- (0) Hazen, T. C. and C. Berry*. 1991. "Bioreactors." Invited Poster, US Department of Energy, Office of Environmental Restoration Technology Information Exchange Workshop, Augusta, GA.
- (0) Hazen, T. C. 1991. "Ex-Situ Bioremediation of SRS Waste Sites." Invited Speaker, US Department of Energy, Office of Environmental Restoration Technology Information Exchange Workshop, Augusta, GA.
- (0) Hazen, T. C. 1991. "In-Situ Bioremediation of SRS Waste Sites." Invited Speaker, US Department of Energy, Office of Environmental Restoration Technology Information Exchange Workshop, Augusta, GA.
- (0) Hazen, T. C. 1991. "SRS Integrated Demonstration: Bioremediation Tasks." Invited Seminar/Convener, Fourth International Institute for Gas Technology Symposium on Gas, Oil, Coal and Environmental Biotechnology, Colorado Springs, CO.
- (5) (all in folder) Hazen, T. C., L. Jimenez, G. Lopez de Victoria, and C. B. Fliermans. 1991. "Comparison of Bacteria from Deep Subsurface Sediment and Adjacent Groundwater." Microb. Ecol. 22: 293-304.
- (2) (all in folder) Hazen, T. C. and L. Jimenez. 1988. "Enumeration and Identification of Bacteria from Environmental Samples Using Nucleic Acid Probes." Microbiological Sciences. 5(11): 340-343.
- (6) (all in folder) Jimenez, L. 1990. "Molecular Analysis of Deep-Subsurface Bacteria." Appl. Environ. Microbiol. 56(7): 2108-2113.
- (1) Jimenez, L. 1989. "Molecular Analysis of Deep Subsurface Bacteria." WSRC-RP-89-1039. Thesis for Submission to the Intercampus Doctoral Committee Puerto Rico Resource Center for Science and Engineering.
- (5) (all in folder) (1 of abs also) Lombard*, K. H., J. Borthen, and T. C. Hazen. 1993 "The Design and Management of System Components for *in situ* Methanotrophic Bioremediation of Chlorinated Hydrocarbons." In Situ and On-Site Bioreclamation, The Second International Symposium, San Diego, CA. (paper in press). WSRC-MS-92-454.

- ***Looney, B. B., T. C. Hazen, D. S. Kaback, and C. A. Eddy. 1991. "Full-Scale Field Test of the In Situ Air Stripping Process at the Savannah River Integrated Demonstration Test Site." WSRC-RD-91-22.
- (1) Lopez de Victoria, G. 1989. "Chemotactic Behavior of Deep Subsurface Bacteria Toward Carbohydrates, Amino Acids, and a Chlorinated Alkene." DP-1779. Thesis Submitted for Degree of Master of Science at University of Puerto Rico.
- ***Morrissey, C. M., S. E. Herbes, A. V. Palumbo*, T. J. Phelps, and T. C. Hazen. 1993. "Use of Laboratory Soil Columns to Optimize In Situ Biotransformation of Tetrachloroethylene." [abs] Invited Seminar Speaker, In Situ and On-Site Bioreclamation, The Second International Symposium, San Diego, CA. (paper in press).
- (5) (all in folder) Pfaender, F. K. and S. C. Long. 1993. "Toxicity Changes Accompanying In Situ Bioremediation." [abs] Invited Seminar Speaker, In Situ and On-Site Bioreclamation, The Second International Symposium, San Diego, CA. (paper in press).
- (5) Wear Jr., J. E. 1993. "Environmental Diagnostic Analysis of Ground Water Bacteria and Their Involvement in Utilization of Aromatic Compounds." WSRC-TR-93-083. Thesis Submitted to the Graduate Faculty of Wake Forest University.

SR 121107: Remediation

- (1) Harrold, R. T., T. S. Snyder, and R. S. Kasevich. 1993. "In Situ Radio Frequency Soil Remediation Heating Demonstration." Westinghouse STC Report No. 93-9TDO-RFHET-R1.
- (5) (all in folder) Haselow, J. S., J. Rossabi, T. Jarosch. 1992. "Emerging Technologies for Abatement of Atmospheric Chlorinated Volatile-Organic Compound Emissions." Proceedings of the 1992 Waste Management and Environmental Sciences Conference, San Juan Puerto Rico.
- (5) Looney, B. B., J. B. Pickett and J. J. Malot. 1991. "Pilot Test of a Vacuum Extraction System for Environmental Remediation of Chlorinated Solvents at the Savannah River Site." WSRC-RD-91-19.
- (5) Rossabi, J., J. S. Haselow. 1991. "Technology Status Report: Off-Gas Treatment Technologies for Chlorinated Volatile Organic Compound Air Emissions." WSRC-RP-91 0603.
- (0) Westinghouse Savannah River Company. 1991. "Air Pollution Control Feasibility Study." Prepared in support of an Air Permit Application to the South Carolina Department of Health and Environmental Control.
- (0) Yamazaki-Nishida, S., H. W. Read, J. K. Nagano, T. Jarosch, C. Eddy, S. Cervera-March, and M. A. Anderson. 1992, in preparation. "Photodegradation of Volatile Chlorinated Compounds by Using TiO₂ Pellets from a Soil Vapor Extraction Treatment Unit."

SR 131001: Remediation

- (0) Westinghouse Savannah River Company. 1992. "In-Situ Radio Frequency Heating Demonstration Field Test Plan." WSRC-RP-92-1428.

SR 121103: Operations and Management

- (9) (all in folder) Steele, J. L., D. S. Kaback, and B. B. Looney. 1992. "Organics in Soils and Groundwater at Non-Arid Sites (A-1) Integrated Demonstration." Presented at Spectrum '92 Conference, Boise, ID.
- (21) (all in folder) U. S. Department of Energy Environmental Restoration and Waste Management Office of Technology Development. 1991. "Cleanup of VOCs in Non-Arid Soils - The Savannah River Integrated Demonstration."
- (1) Walton, T. L. 1991. "Integrated Demonstration for Cleanup of Organics in Soils and Groundwater at Non-Arid Sites." IDP-0566.
- (1) Westinghouse Savannah River Company. 1992. "Roadmap for the Integrated Demonstration for Cleanup of Organics in Soils and Groundwater at Non-Arid Sites at the Savannah River Site." SRT-EMP-92-0204.
- (14) (all in folder) Westinghouse Savannah River Company Environmental Restoration. 1993. "M Area HWMF Fact Sheet."

DRAFT

**TRIP REPORT
PARTITIONING TRACER TESTING
INTERA AND THE UNIVERSITY OF TEXAS
AUSTIN, TEXAS**

A.4.1 SITE VISIT

Intera, Inc. (Intera), in cooperation with the University Texas at Austin (UT), is developing an NAPL-partitioning tracer test (NPTT) for the detection and estimation of non-aqueous phase liquid (NAPL) and assessment of remediation at NAPL sites. A site visit was conducted by Mr. Paul Favara, P.E. of Environmental Science & Engineering, Inc. (ESE), at INTERA and the UT laboratory where tracer testing is being accomplished. The purpose of the site visit was to investigate the applicability of NPTT for the detection of dense non-aqueous phase liquids (DNAPL) at the Study Area. Although the methods presented herein are equally applicable to light-NAPL, the focus of discussion will be on DNAPL as it is the greatest concern at the site. During the site visit, Mr. Favara met with Dr. Richard Jackson of Intera and Dr. Gary Pope of UT.

A.4.2 OBSERVATIONS

The site visit opened with a presentation by Dr. Richard Jackson of INTERA. The presentation addressed the feasibility of using partitioning tracers for the purposes of estimating the location and quantity of DNAPL. The paragraphs below summarize the details of the technology.

Subsurface partitioning tracer testing for the detection of DNAPL is an emerging technology. The objective of the technology is to determine the quantity and type of DNAPL present in the sub-surface and is applicable to both saturated and unsaturated soils. The characterization of DNAPL contamination in aquifers involves the location of DNAPL zones and the estimation of the amounts of DNAPL within the zones. There are currently four different methods of DNAPL characterization available for site investigations (Jin et al., 1994):

1. Core Sampling,
2. Cone Penetrometer Testing,
3. Geophysical Loggings, and
4. Tracer Test Methods.

The limitations with core sampling, cone penetrometer testing, and geophysical logging methods involve the size of the sample with respect to the area of interest. When site characterization data indicates there is a high potential for the presence of DNAPL, methods 1, 2, and 3 above would provide limited probability of detecting DNAPL, as it is possible that the intrusive investigation may entirely miss the location of the DNAPL. The advantage of NPTT is that its "sample" is much larger with respect to site area than the previously referenced methods. Thus, NPTT sample a much larger volume of porous medium than do core sample or geophysical logs. Consequently, the DNAPL saturation estimated from tracer data represents an average over a larger volume.

Tracers are developed specifically for each site location. Developmental requirements only include a sample of the soils from the zone from where testing will be conducted. These soil samples are then tested in a laboratory where optimal tracers and application concentrations will be determined for the full-scale site characterization test.

Although NPTT is a new field with respect to detection of environmental contaminants, the methods are adapted from partitioning interwell tracer tests (PITT) used in the field of petroleum engineering. The advantage PITT has over methods core sampling, cone penetrometer testing, and geophysical loggings is that it is more effective in locating subsurface DNAPL pools, lenses, and residual, can estimate the DNAPL saturation, and can provide a means of assessing the performance of DNAPL remediation systems.

Tracers can be added to fluids in low concentration and used to follow their movement without affecting their physical properties. The PITT consists of the simultaneous injection of several tracers with different partition coefficients at one or more injection wells and the subsequent measurement of tracer concentrations at one or more production or monitor wells. When tracers with different partition coefficients are injected into the aquifer, the nonpartitioning tracers only stay in the water phase (or gas phase in the case of the vadose zone) and move with the velocity of the water while the molecules of partitioning tracers move back and forth between the water and DNAPL phases. When the tracer molecules are in the water phase they move with the velocity of the water and when they are in the DNAPL phase they move with the velocity of the DNAPL. If the DNAPL is at residual saturation, the tracer molecules move only in the water phase. The net result is that the partitioning tracer pulse lags behind the nonpartitioning tracers moving with the water front. The extent of the separation of the tracer pulses (i.e., at the extraction wells) depends on the fraction of time the tracer spends in the DNAPL phase compared to that in the water, which is a function of DNAPL saturation and the partition coefficient. The greater the chromatographic separation of the tracers, the greater the DNAPL saturation. Figure A.4-1 presents an example of the tracer test response showing tracer eluting at different times, for a simulated aquifer contaminated with PCE. By analyzing the production well tracer response, the amount of residual DNAPL in the subsurface environment can be determined. A simple method to analyze the tracer response is the method of moments (Himmelblau, 1968) and can be used to estimate the level of DNAPL between and injection and extraction well in an interwell test (or in the radius of a single well using a single well test). The specific numerical methods used to analyze and interpret the data are presented in Reference 1.

NPTT can also be used to assess the effectiveness of a DNAPL remediation program in much the same way that it is used to detect DNAPL during the characterization phases of a project, provided the level of DNAPL present had

been quantified prior to remediation. NPTT can be conducted after remediation has started to assess the level of DNAPL remaining in the system. Thus, if pre-remediation DNAPL levels are known, the degree of treatment to date can be assessed. If pre-remediation DNAPL levels are not known, the tests are still useful in that they can be used to quantify how much DNAPL remains and thus be used to estimate the life of a DNAPL remediation project.

NPTT can be conducted using a single-well (Figure A.4-2), in which the area in the vicinity of the well is flooded with a solution containing the tracer. After the flood, water is extracted from the well and chemical analysis is performed to quantify the concentrations of tracer present. With the interwell method (Figure A.4-3), the tracer is injected into the injection wells and extracted using extraction wells. Water from the extraction well(s) is analyzed in the same manner as water from the single well test. Both well methods have been used extensively in the petroleum industry to estimate residual oil saturation prior to the beginning of enhanced oil recovery operations. The technology is advanced; single-well tests have been applied to over 300 oil field reservoir throughout the world in an extreme variety of settings. The strengths and weaknesses of the tests have been determined and the latter remedied by improved tracers and well layout designs. However, the conventional application of single-well tracer test technology to aquifers suffers from the principal drawback of geophysical loggings and coring, namely, that the single well must penetrate very near a DNAPL contamination for it to be effective. Consequently, the INTERA/UT team has concentrated research on interwell partitioning tracer tests. With both well methods, the wells have to be screened in the layer where the NAPL is present for the tracer to interact with the DNAPL and thus, for the test to provide meaningful and useful data.

Following Dr. Jackson's presentation, Paul Favara and Richard Jackson met with Dr. Gary Pope in his office at UT. A tour of the laboratory where tracers are developed and tested was given by Mr. Paul Mariner. At the time of the site

visit, tracers for an unsaturated zone test at Sandia National Laboratories were being developed using a 1-inch core sample , of 2-feet in length. Air-flow from this core sample was immediately passed to a gas chromatograph equipped with a thermal resistivity detector to provide real time data on tracer performance.

A.4.3 CONCLUSIONS

The use of partitioning tracers to characterize DNAPL at waste sites is a new and emerging technology. The technology has the potential of filling a void in site characterization efforts with respect to identifying the location and amount of DNAPL in the subsurface. With the knowledge of amount and location of DNAPLs, remediation efforts can be further refined to consider more than just the dissolved fraction of a constituent in the subsurface and allow better estimates of solute transport and O&M costs for remediation.

A.4.4 RECOMMENDATIONS

The used of partitioning tracers would be appropriate in the Window Area, which is interpreted to be in a low lying area of the alluvial system and an area suspected to contain DNAPL. Implementation of NPTT in this area could estimate the volume and location of DNAPL in this area. Characterization of DNAPL in this area is crucial as it is hydraulically connected to the Paluxy Aquifer. Dr. Jackson estimates that initial testing of the Window Area may cost approximately \$300,000 for a single test. However, due to economies of scale associated with wells installed and mobilization of field equipment and personnel, subsequent tests could be performed for significantly less cost.

NPTT may also be appropriate in the vadose zone beneath Building 181. In-situ vapor extraction (ISV) tests conducted between December 1993 and March 1994 have indicated a high level of TCE present in the area. The use of NPTT in this area could help to define the full extent of DNAPL in the vadose zone. This information could then be used to optimize the proposed expansion of the ISV system as well as being a basis for estimating the magnitude (with respect to

cost and time) of remedial efforts required at Building 181. Partitioning tracer tests for the saturated zone in Building 181 may also be warranted to determine the level of DNAPL present in the alluvial system this area.

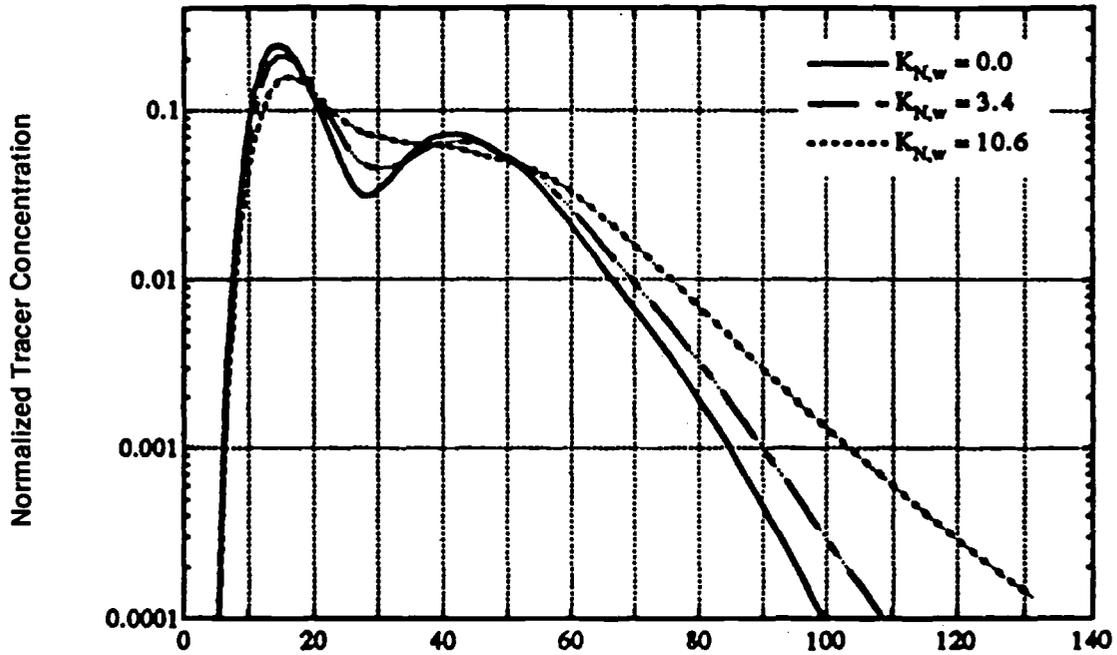


Figure A.4-1
PRODUCTION WELL TRACER RESPONSE
CURVES BEFORE SURFACTANT REMEDIATION

SOURCE: ESE, 1994.



Environmental
Science &
Engineering, Inc.

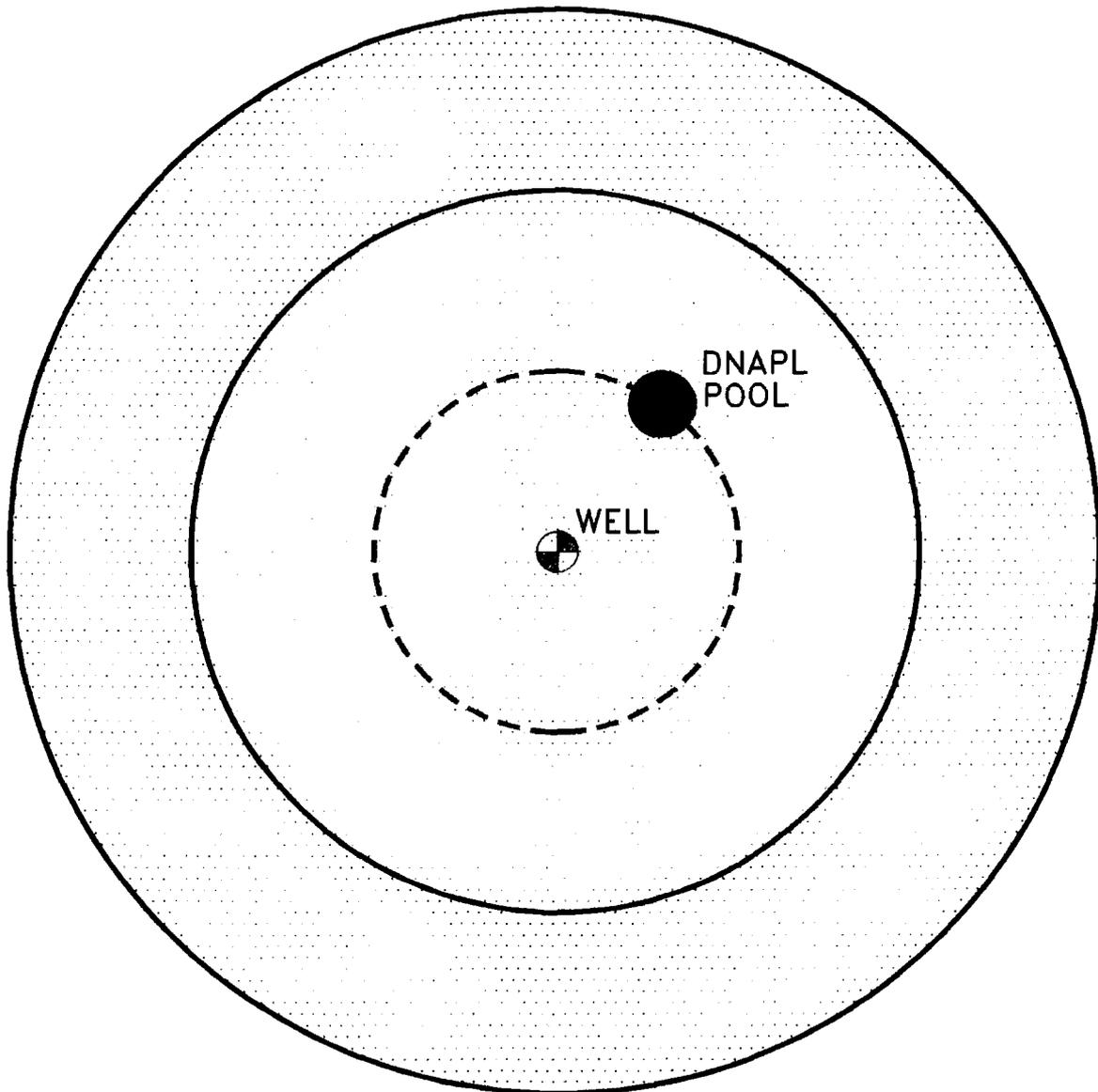


Figure A.4-2
SINGLE-WELL PARTITIONING TRACER TEST
AFP4 AND CAFB
FORT WORTH, TEXAS
SOURCE: ESE, 1994.



Environmental
Science &
Engineering, Inc.

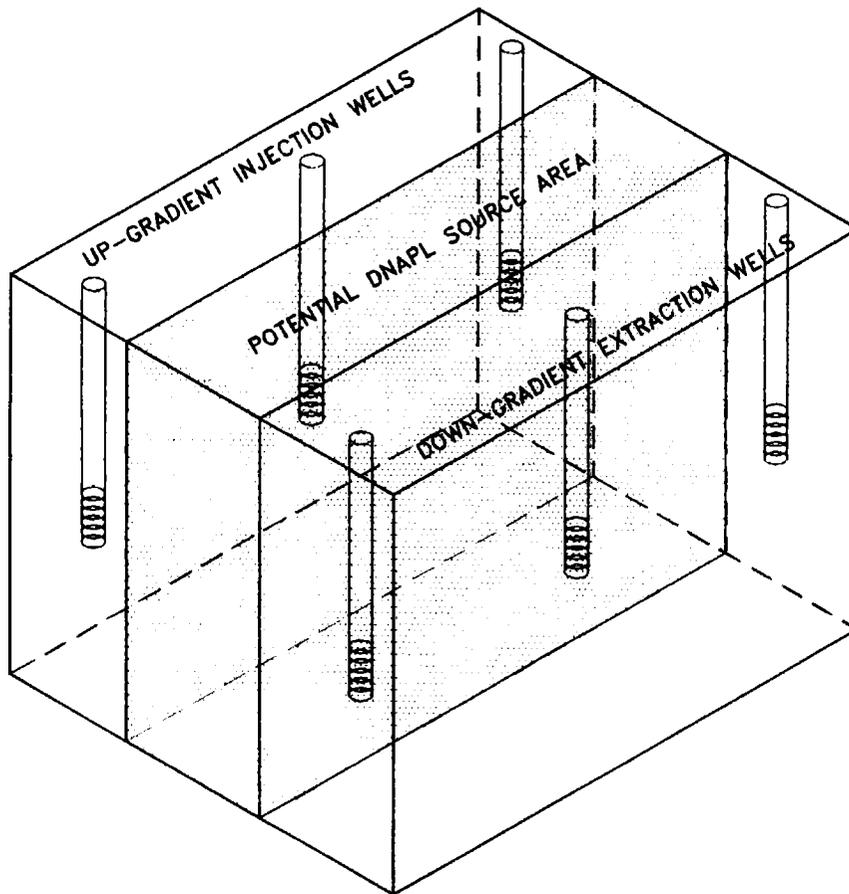


Figure A.4-3
POTENTIAL CONFIGURATION OF INTERWELL
PARTITIONING TRACER TEST
AFP4 AND CAFB, FORT WORTH, TEXAS
SOURCE: ESE, 1994.



Environmental
Science &
Engineering, Inc.

A DILCORP Company

REFERENCES FOR APPENDIX A

New VOC Removal Technology Eliminates Carbon--and its Costs, Industrial Wastewater, pp. 46-47, March/April 1994.

Jin, M., Delshad M., McKinney, D.D., Pope, G.A., Sepehrnori, K., Tilburg, C., and Jackson, R.E. 1994. Subsurface NAPL Contamination: Partitioning Tracer Test for Detection, Estimation, and Remediation Performance Assessment; American Institute of Hydrology "Toxic Substances and the Horologic Sciences" April 10-13, 1994.

224137

FINAL PAGE

ADMINISTRATIVE RECORD

FINAL PAGE

FINAL PAGE

ADMINISTRATIVE RECORD

FINAL PAGE