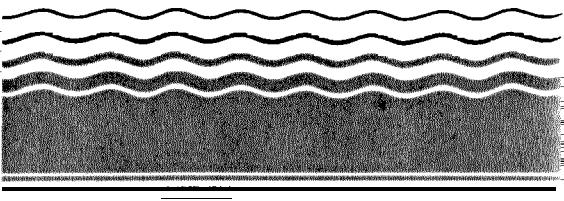
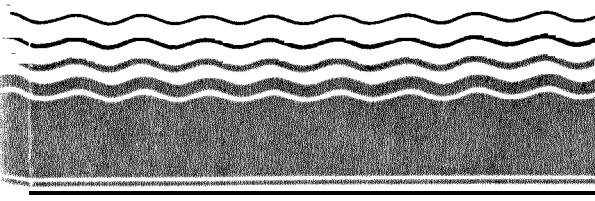
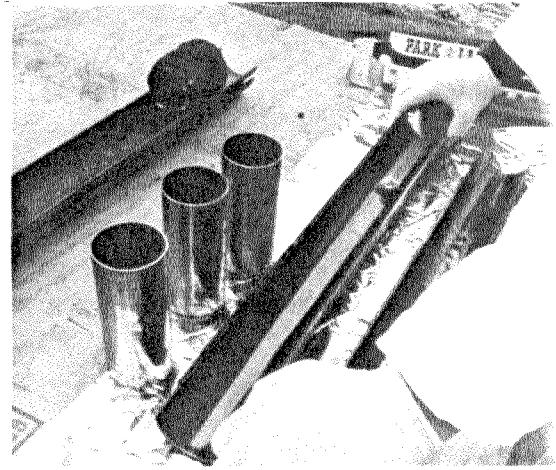
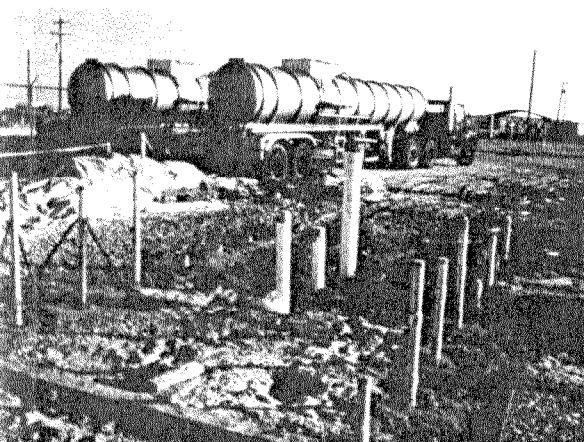
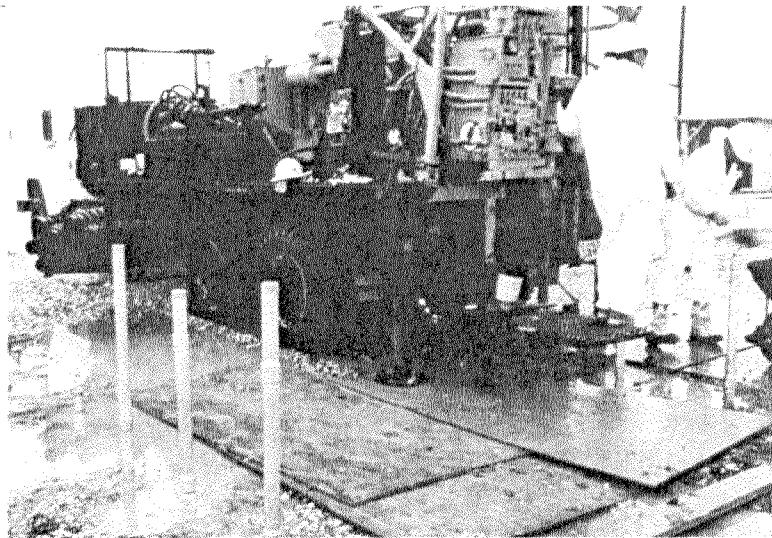
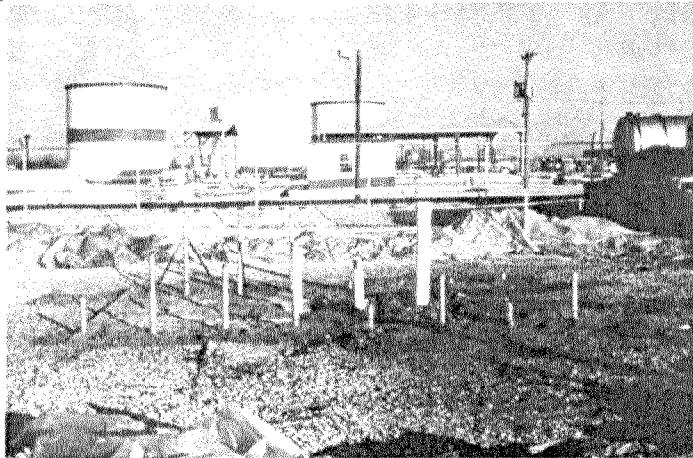




IITRI Radio Frequency Heating Technology

Innovative Technology Evaluation Report



CONTACT

Laurel Staley is the EPA contact for this report. She is presently with the newly organized National Risk Management Research Laboratory's new Land Remediation and Pollution Control Division in Cincinnati, OH (formerly the Risk Reduction Engineering Laboratory). The National Risk Management Research Laboratory is headquartered in Cincinnati, OH, and is now responsible for research conducted by the Land Remediation and Pollution Control Division in Cincinnati.

IITRI RADIO FREQUENCY HEATING TECHNOLOGY
INNOVATIVE TECHNOLOGY EVALUATION REPORT

NATIONAL RISK MANAGEMENT RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

NOTICE

The information in this document has been funded by the U.S. Environmental Protection Agency (EPA) under the auspices of the Superfund Innovative Technology Evaluation Program under Contract No. 68-C0-0048 to Science Applications International Corporation. Mention of trade names or commercial products does not constitute an endorsement or recommendation for use.

FOREWORD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet these mandates, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on methods for the prevention and control of pollution to land, air, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites and groundwater; and prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

The Laboratory's Superfund Innovative Technology Evaluation (SITE) Program was authorized in the 1986 Superfund Amendments. The program is a joint effort between EPA's Office of Research and Development (ORD) and Office of Solid Waste and Emergency Response. The purpose of the program is to enhance the development of hazardous waste treatment technologies necessary for implementing new cleanup standards that require greater reliance on permanent remedies. This is accomplished by performing technology demonstrations designed to provide engineering and economic data on selected technologies.

The project described in this document consisted of an evaluation of the IIT Research Institute (IITRI) in situ radio frequency heating (RFH) technology. As a part of this evaluation, a Demonstration Test was conducted by the SITE Program in coordination with research efforts sponsored by the US. Air Force. During the demonstration, the IITRI in situ RFH system was used to treat thermally a volume of soil 14.1 feet (4.30 meters) long, 10.0 feet (3.05 meters) wide, and 24.0 feet (7.32 meters) deep. The goals of the study, summarized in this Innovative Technology Evaluation Report, are: 1) to assess the ability of in situ RFH to remove organic contaminants from a contaminated site at Kelly Air Force Base in San Antonio, TX, and 2) to develop capital and operating costs for the technology.

This publication has been produced as part of the NRMRL's strategic long-term research plan. It is published and made available by ORD to assist the user community and to link researchers with their clients. Additional copies of this report may be ordered at no charge from ORD Publications, G-72 (refer to the EPA document number found on the report's front cover): (phone) 513-569-7562, (fax) 513-569-7566, (mail) 26 West Martin Luther King Dr., Cincinnati, OH, 45268. Once this supply is exhausted, copies can be purchased from the National Technical Information Service, 5285 Port Royal Rd, Springfield, VA, 22151, 800-553-6847. Reference copies will be available in the Hazardous Waste Collection at EPA libraries. To obtain further information regarding the SITE Program and other projects within SITE, telephone 513-569-7696.

E. Timothy Oppelt, Director
National Risk Management Research Laboratory

TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
Notice	ii
Foreword	iii
List of Tables	viii
List of Figures	ix
Abbreviations	x
Acknowledgments	xii
Executive Summary	xiii
1. Introduction..	1
1.1 Background	1
1.2 Brief Description of Program and Reports	4
1.3 Purpose of the ITER	6
1.4 Technology Description	6
1.5 Key Contacts	13
2. Technology Applications Analysis	15
2. Objectives - Performance Versus Applicable or Relevant and Appropriate Regulations (ARARs)	15
2.1.1 Comprehensive Environmental Response, Compensation, and Liability Act	15
2.1.2 Resource Conservation and Recovery Act	18
2.1.3 Clean Air Act	19
2.1.4 Safe Drinking Water Act	19
2.1.5 Clean Water Act	19
2.1.6 Toxic Substances Control Act	20
2.1.7 Occupational Safety and Health Administration Requirements	20
2.2 Operability of the Technology	21
2.3 Applicable Wastes	23
2.4 Key Features of the IITRI RF Heating Technology	24
2.5 Availability and Transportability of the System	24
2.6 Materials Handling Requirements	25
2.7 Site Support Requirements	25
2.8 Limitations of the Technology.....	26
2.9 References	28

TABLE OF CONTENTS (CONTINUED)

<u>Section</u>		<u>Page</u>
3. Economic Analysis		29
3.1 Introduction		29
3.2 Basis of Economic Analysis		29
3.3 Issues and Assumptions		30
3.3.1 Site Preparation Costs		33
3.3.2 Permitting and Regulatory Costs		33
3.3.3 Equipment Costs		33
3.3.4 Startup and Fixed Cost		35
3.3.5 Operating Costs for Treatment		37
3.3.6 Cost for Supplies		38
3.3.7 Cost for Consumables		38
3.3.8 Cost for Effluent Treatment and Disposal		38
3.3.9 Residuals and Waste Shipping, Handling, and Transport Costs		39
3.3.10 Cost for Analytical Services		39
3.3.11 Facility Modification, Repair and Replacement Costs		39
3.3.12 Site Demobilization Costs		40
3.4 Results of the Economic Analysis		40
3.5 References		42
4. Treatment Effectiveness		43
4.1 Background		43
4.2 Methodology		46
4.2.1 Soil Sampling		46
4.2.2 Groundwater Sampling		56
4.2.3 SVE Vapor Stream Sampling		56
4.3 Performance Data		56
4.3.1 Results of Chemical Analyses		57
4.3.2 Physical Analyses		61
4.4 Residuals		63
4.5 References		64
5. Other Technology Requirements		65
5.1 Environmental Regulation Requirements		65
5.2 Personnel Issues		65

TABLE OF CONTENTS (CONTINUED)

<u>Section</u>	<u>Page</u>
5.3 Community Acceptance	66
5.4 References	67
6. Technology Status	68
Appendix A: Supplementary Data	69
A.1 Chemical Analyses	69
A. 1.1 Procedure for Selecting Contaminants for Statistical Evaluation	69
A. 1.2 Methodology for Statistical Evaluation	74
A.1.3 Data Summary.....	76
A.2 Physical Analyses	116
A.2.1 Particle Size Distribution	116
A.3 Operational Data	123
A.3.1 Temperature	123
A.3.2 SVE System Operation	125
A.3.3 Dewatering System Operation	127
A.3.4 Electric Usage	129
A.3.5 RF Emissions	129
Appendix B: Case Studies	130
B. 1 Volk Air National Guard Base (ANGB)	130
B.2 Rocky Mountain Arsenal (RMA)	131
B.3 References	131
Appendix C: Vendor Claims	132
C.1 Introduction	132
C.2 Process Description	133
C.3 Treatability Studies	136
C.4 Field Experiments	136
C.4.1 Kelly Demonstration	136
C.5 Current Status and Future Plans	140
C.6 References	141

LIST OF TABLES

<u>Number</u>		<u>Page</u>
1	Criteria Evaluation for the IITRI RFH Technology	xvii
2	Potential Federal and State ARARs for the Treatment of Contaminated Soil by the IITRI RFH System at a Superfund Site	16
3	Twelve Cost Categories for the IITRI SITE Demonstration Economic Analysis	30
4	Summary of IITRI RFH Equipment Costs	35
5	Treatment Costs for the IITRI RF System Treating 10,152 Tons of Soil (Scaled-up from the Results of the SITE Demonstration)	41
6	Treatment Costs for the IITRI RF System Treating 8,640 Tons of Soil (Based Upon a Theoretical RF Design and Treatment Zone)	42
7	Summary of Number of QA Samples Analyzed	54
8	Number of Soil Samples Taken During the SITE Demonstration	55
9	Number of Complete Matched Pairs for the Soil Sample	55
10	Summary of Particle Size Distribution Data	63
11	Radio Frequency Radiation TLVs	67

LIST OF FIGURES

<u>Number</u>		<u>Page</u>
1	Regional Maps Showing Demonstration Location	2
2	Plan View of the Demonstration Site	3
3	Basic Schematic of the IITRI RFH System	7
4	Relative Locations of Subsurface Components Used in the IITRI RFH System	8
5	Cross-section of IITRI's RFH System (Not to Scale)	11
6	SITE Demonstration Monitoring and Dewatering Wells	47
7	SITE Demonstration Boreholes	50
8	Borehole Sampling Depths	51

ABBREVIATIONS

AC	alternating current	EPA	Environmental Protection Agency
ACGIH	American Conference of Government and Industrial Hygienists	FCC	Federal Communications Commission
AFB	Air Force Base	FID	flame ionization detector
ANGB	Air National Guard Base	GHz	gigahertz
ARAR	Applicable or Relevant and Appropriate Requirement	IITRI	IIT Research Institute
ASTM	American Society for Testing and Materials	ISM	industrial, scientific, and medical
ATTIC	Alternative Treatment Technology Information Center	ITER	Innovative Technology Evaluation Report
bgs	below ground surface	kW	kilowatt
B&RE	Brown and Root Environmental	LDRs	land disposal restrictions
CAA	Clean Air Act	MCL	Maximum Contaminant Level
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act	MDL	Method Detection Limit
CERI	Center for Environmental Research Information	MHz	megahertz
CFR	Code of Federal Regulations	MS/MSD	matrix spike/matrix spike duplicate
CI	confidence interval	NAAQS	National Ambient Air Quality Standards
CLU-IN	cleanup information	NIOSH	National Institute for Occupational Safety and Health
CPR	cardiopulmonary resuscitation	NPDES	National Pollutant Discharge Elimination System
CWA	Clean Water Act	ORD	Office of Research and Development
DOT	Department of Transportation	OSC	on-scene coordinator
		OSHA	Occupational Safety and Health Administration

ABBREVIATIONS (CONTINUED)

OSWER	Office of Solid Waste and Emergency Response	SAIC	Science Applications International Corporation
PCB	polychlorinated biphenyl	SARA	Superfund Amendments and Reauthorization Act
POTW	Publicly-Owned Treatment Works	SDWA	Safe Drinking Water Act
PPE	personal protective equipment	SITE	Super-fund Innovative Technology Evaluation
ppm	parts per million	SVE	soil vapor extraction
PQL	practical quantitation limit	s v o c	semivolatile organic compound
PVC	polyvinyl chloride	TLV	Threshold Limit Value
QA/QC	quality assurance/quality control	TPH	total petroleum hydrocarbons
QAPP	Quality Assurance Project Plan	TRPH	total recoverable petroleum hydrocarbons
RCRA	Resource Conservation and Recovery Act	TSD	Treatment, Storage, and Disposal
RF	radio frequency	TSCA	Toxic Substances Control Act
RFH	radio frequency heating	USAF	U.S. Air Force
RI/FS	remedial investigation/feasibility study	VISITT	Vendor Information System for Innovative Treatment Technologies
RMA	Rocky Mountain Arsenal	VOC	volatile organic compound
RPM	remedial project manager		
RREL	Risk Reduction Engineering Laboratory		

ACKNOWLEDGMENTS

This report was prepared under the direction and coordination of Laurel Staley, Environmental Protection Agency (EPA) Superfund Innovative Technology Evaluation (SITE) Work Assignment Manager in the Risk Reduction Engineering Laboratory (RREL), Cincinnati, Ohio. EPA-RREL contributors and reviewers for this report were Michelle Simon, Teri Richardson, and Robert Stenburg. Harsh Dev of the IIT Research Institute also contributed to and reviewed the document.

This report was prepared for EPA's SITE Program by the Technology Evaluation Division of Science Applications International Corporation in Cincinnati, Ohio under Contract No. 68-C0-0048. This report was written by Sharon Krietemeyer and Eric Saylor. The Work Assignment Manager for the project was Jim Rawe.

EXECUTIVE SUMMARY

This document is an evaluation of the performance of the IIT Research Institute (IITRI) in situ radio frequency heating (RFH) technology and its ability to remediate soil contaminated with organics. Both the technical and economic aspects of the technology are examined.

A demonstration of IITRI's in situ RFH system was conducted by the U.S. Environmental Protection Agency (EPA) Superfund Innovative Technology Evaluation (SITE) Program from January 1993 to August 1993 at Site S-1 at Kelly Air Force Base (AFB) in San Antonio, Texas. IITRI's RFH system applies radio frequency (RF) energy to soil through exciter electrodes, thereby creating molecular agitation that heats the soil along with water and contaminants contained within the soil. The IITRI RFH technology has two primary functions: (1) to heat the soil by transmitting RF energy into it and (2) to collect vapors from the volatilized contaminants in the heated soil. It is important to remember that the design of the soil vapor extraction (SVE) system is crucial to enable the IITRI RFH technology to remove contaminants from soil. For this demonstration, the SVE extraction wells were an integral part of IITRI's system; this may not be the case in the future if the SVE design is modified.

The demonstration began with initial soil sampling conducted from January 25, 1993 through February 6, 1993, during the installation of the underground system components. RF energy was applied to the soil from April 3, 1993 through June 3, 1993. The soil was allowed to cool for approximately 2 months, and final sampling was conducted from August 16, 1993 to August 19, 1993. Based on the analytical results from soil samples collected before and after treatment, conclusions were reached concerning the technology's ability to remove petroleum hydrocarbons and specific organic contaminants from soil.

Shallow groundwater (approximately 24 feet, or 7.3 meters below ground surface) encountered within the treatment zone during system installation, in addition to design problems encountered during the demonstration, resulted in a smaller soil treatment volume than was originally specified in the Demonstration Plan. This smaller volume, approximately 122 cubic yards (93.3 cubic meters), is referred to as the "revised design treatment zone." To compensate for the shallow groundwater, the exciter electrodes were shortened and a dewatering system was installed. Despite these measures, IITRI believes that shallow groundwater during the demonstration caused the RFH system to malfunction, resulting in excessive soil temperatures near the exciter

electrodes and much lower temperatures near the edges of the revised design treatment zone. It was not possible to monitor groundwater levels below the revised design treatment zone during treatment, but nearby groundwater level measurements obtained during this period ranged from 24 to 33 feet (7.3 to 10 meters) below ground surface. The portion of the revised design treatment zone that achieved the target soil temperature of 150°C (302°F) during the demonstration had a volume of approximately 45 cubic yards (34.4 cubic meters) and is referred to as the “heated zone.”

The goal of this demonstration was to evaluate the ability of the IITRI RFH technology to remove contaminants from in situ soil. Determination of whether the technology met the goal was based upon contaminant concentration changes in the pre- and post-treatment samples. Concentration data from the original design treatment zone were subjected to a preliminary statistical evaluation. Contaminants that were found to have statistically significant concentration changes at a confidence level of 80 percent or greater in the preliminary evaluation were statistically evaluated for the revised design treatment zone. Only contaminants that exhibited a statistically significant concentration change at a confidence level of 90 percent or greater during the final statistical evaluation were used to draw conclusions. Changes in total recoverable petroleum hydrocarbon (TRPH) concentrations, semivolatile organic compounds (SVOCs), and volatile organic compounds (VOCs) were evaluated for this demonstration.

Prior to the demonstration, concentrations of TRPH and certain individual SVOCs and VOCs were designated as “critical” measurements. Concentrations of all other SVOCs and VOCs were considered “noncritical” measurements. The critical SVOCs and VOCs were selected based on preliminary data and pretreatment sampling results from Site S-1. The critical SVOCs were 1,2-dichlorobenzene; 1,3-dichlorobenzene; 1,4-dichlorobenzene; 2-methylnaphthalene; and naphthalene. The critical VOCs were benzene, toluene, ethylbenzene, chlorobenzene, and total xylenes.

The following results were observed for TRPH and SVOCs within the revised design treatment zone:

- There was a statistically significant decrease in TRPH concentration at the 95 percent confidence level; the estimated decrease in the mean concentration was 60 percent.

- None of the five critical SVOCs achieved a statistically significant change during the preliminary evaluation and, therefore, were not evaluated for the smaller revised design treatment zone.

- Pyrene and bis(2-ethylhexyl)phthalate were the only noncritical SVOCs that exhibited changes in the preliminary and final statistical evaluations. They exhibited a change in concentration at the 97.5

percent confidence level; estimated decreases in the mean concentrations were 87 and 48 percent, respectively.

The decreases in TRPH and SVOCs were likely due to some combination of the RF energy and SVE applied to the soil. RFH increased the temperature of the soil, along with water and contaminants contained within the soil, thereby volatilizing (to varying degrees) SVOCs and certain components of TRPH. SVE, which was used to remove the volatilized contaminants, also enhances vaporization. Decreases in TRPH and SVOC may also have been caused by the degradation of these compounds from soil temperatures reaching greater than 1,300°C (2,372 °F) near the exciter electrodes. Decreases from outward migration are unlikely, since the configuration of the SVE system limits this type of migration.

For the VOCs within the revised design treatment zone, the following results were observed:

- Chlorobenzene was the only critical VOC that achieved a statistically significant concentration change in the preliminary statistical evaluation; it did not achieve a statistically significant change in the final statistical evaluation. No plausible theories have been developed to explain the fact that chlorobenzene did not exhibit a statistically significant decrease in the revised design treatment zone.
- There were statistically significant increases in the concentrations of four noncritical VOCs (all ketones) at the 99 percent confidence level; estimated increases in the mean concentrations were: 457 percent for 2-hexanone; 263 percent for 4-methyl-2-pentanone; 1,073 percent for acetone; and 683 percent for methyl ethyl ketone.

The ketones may have been formed by the degradation and subsequent oxidation of TRPH near the exciter electrodes, where soil temperatures were highest. A possible degradation pathway may be the pyrolytic conversion of TRPH to unsaturated hydrocarbons. In the presence of a catalyst (e.g., silica in the soil), the RF energy may convert these hydrocarbons into ketones. Alternatively, the increase in ketones may also have been caused by inward migration from sources such as the groundwater and the soil beyond the sampled area. There are insufficient data to confirm or disprove either of these hypotheses.

Outside the revised design treatment zone, only TRPH showed a statistically significant change at the 95 percent confidence level, with an estimated 88 percent mean concentration increase. Because the treatment area was under a vacuum due to the SVE system, the TRPH increase may have resulted from inward migration; it is not likely to be due to outward migration.

The following results were observed within the heated zone:

- There was a statistically significant decrease in TRPH concentration at the 97.5 percent confidence level; the estimated decrease in the mean concentration was 95 percent.
- None of the critical or noncritical SVOCs exhibited a statistically significant change in the final evaluation.
- None of the critical or noncritical VOCs exhibited a statistically significant change in the preliminary or final evaluations.

The TRPH decrease may be from the SVE system pulling the volatilized contaminants out of the heated zone into vacuum wells. As in the revised design treatment zone, this decrease may also have been caused by the degradation of these compounds from the elevated temperatures of the RFH system.

Outside of the heated zone, there was a statistically significant decrease in the concentration of bis(2-ethylhexyl)phthalate at the 90 percent confidence level; the estimated decrease in the mean concentration was 37 percent. This decrease may also have resulted from the some combination of contaminants being volatilized and collected by the SVE system. There were also statistically significant increases at the 99 percent confidence level in the concentrations of four noncritical VOCs (all ketones) outside the heated zone. The estimated mean increases for these four ketones were: 423 percent for 2-hexanone; 249 percent for 4-methyl-2-pentanone; 1,347 percent for acetone; and 1,049 percent for methyl ethyl ketone. As previously discussed, these ketones may have been formed by the degradation and subsequent oxidation of TRPH or may have migrated inward from the groundwater or surrounding soil.

Two-dimensional modeling of gas flow rates was used to qualitatively evaluate inward migration and treatment zone extraction rates. The results of this modeling indicate inward gas flows from the area outside the extraction wells toward those wells. Outward flows toward the extraction wells were indicated for much of the area inside the revised design treatment zone. Due to inefficiencies in the SVE system design, gas flows between the outer edge of the impermeable cap and the extraction wells were five times greater than those between the two rows of extraction wells. As a result, contaminant migration into the treatment zone was possible, especially near the outer edges, and contaminant removal from the treatment zone may have been relatively slow compared to inward contaminant migration.

Concentrations of TRPH and specific VOCs and SVOCs in the SVE gas stream were monitored by a U.S. Air Force subcontractor and were not part of the SITE demonstration. The appropriateness of the methods

used and the quality of the data are unknown. However, the results appear to indicate qualitatively removals of TRPH and certain VOCs and SVOCs.

Economic evaluations were performed based on the SITE demonstration revised design treatment zone and a theoretical RF design and treatment zone. The theoretical RF design and treatment zone was based upon information provided by the vendor and bench-scale tests. The effectiveness of the theoretical RF design has not been demonstrated on a pilot- or full-scale level. Due to some combination of inefficiencies in the application of the RF energy and the SVE design a lack of contaminant removal was evident during the SITE demonstration. However, the economic evaluation of the IITRI RFH technology assumes the technology will achieve the target temperature and maintain it for the time desired. The target temperature and duration it is to be applied are site-specific.

The results of these evaluations are as follows :

- o Analysis based on the revised design treatment zone — The cost to treat approximately 10,152 tons (9,210 metric tons) of contaminated soil using a proposed full-scale in situ RFH system was estimated by scaling up costs from the revised design treatment zone. Cleanup costs are estimated to be \$370 per ton (\$410 per metric ton) if the system is utilized 95 percent of the time.
- o Analysis based on the theoretical RF design and treatment zone — The cost to treat approximately 8,640 tons (7,838 metric tons) is estimated to be \$195 per ton (\$215 per metric ton) if the system is utilized 95 percent of the time.

The IITRI RFH technology was evaluated based on the nine criteria used for decision-making in the Superfund feasibility study process. Table 1 presents the evaluation.

Table 1. Criteria Evaluation for the IITRI RFH Technology¹

Evaluation Criteria	Performance
Overall Protection of Human Health and the Environment	<input type="checkbox"/> Site-specific treatability studies will be needed to verify the levels of contaminant removal achievable. <input type="checkbox"/> Requires measures to protect workers during installation and operation. <input type="checkbox"/> Additional contaminants may form at high temperatures if not properly designed or operated.
Compliance with Federal ARARs ²	<input type="checkbox"/> Vapor collection and treatment are needed to ensure compliance with air quality standards. <input type="checkbox"/> Construction and operation of onsite vapor treatment unit may require compliance with location-specific ARARs. <input type="checkbox"/> RF generator must be operated in accordance with Occupational Safety and Health Administration and Federal Communications Commission (FCC) requirements.
Long-term Effectiveness and Performance	<input type="checkbox"/> As with all SVE-based systems, the contaminated source may not be adequately removed. <input type="checkbox"/> Involves some residuals treatment (vapor stream).
Reduction of Toxicity, Mobility, or Volume through Treatment	<input type="checkbox"/> Potentially concentrates contaminants, reducing waste volume. <input type="checkbox"/> Potentially reduces contaminant mobility, although downward mobility of contaminants during treatment has not been quantified. <input type="checkbox"/> May partially destroy some contaminants and, in the process, form new contaminants, thereby potentially reducing or increasing toxicity if not properly designed or operated.
Short-term Effectiveness	<input type="checkbox"/> Presents minimal short-term risks to workers and community from air release during treatment. <input type="checkbox"/> No excavation is required, although drilling will disturb the soil to some extent.
Implementability	<input type="checkbox"/> RF generator must be operated in accordance with the National Institute of Occupational Health and Safety (NIOSH) and FCC requirements (a permit may be required). <input type="checkbox"/> Pilot-scale tests have been completed at two other sites to address soil contamination; no full-scale applications to date. <input type="checkbox"/> Because of operational problems experienced during the SITE demonstration, consistent soil heating was not observed.
Cost ^{1,3}	<input type="checkbox"/> Cost evaluation based on the revised design treatment zone is \$370 per ton (\$410 per metric ton). Cost evaluation based on IITRI's theoretical RF design and treatment zone is \$195 per ton (\$215 per metric ton).
State Acceptance	<input type="checkbox"/> No excavation is required, which should improve state acceptance.
Community Acceptance	<input type="checkbox"/> No excavation is required, which should improve community acceptance. <input type="checkbox"/> Potential health effects of RF fields may be an issue.

1 Based upon the results of the SITE demonstration at Kelly AFB.

2 ARAR = Applicable or Relevant and Appropriate Requirement

3 Actual cost of a remediation technology is highly site-specific and dependent on the target cleanup level, contaminant concentrations, soil characteristics, and volume of soil. Cost data presented in this table are based on the treatment of approximately 10,152 tons (9,210 metric tons) of soil (scale-up based on the revised design treatment zone) and 8,640 tons (7,838 metric tons) of soil (based on IITRI's theoretical RF design and treatment zone).

SECTION 1

INTRODUCTION

This section provides background information regarding the U.S. Environmental Protection Agency's (EPA) Superfund Innovative Technology Evaluation (SITE) Program, discusses the purpose of this Innovative Technology Evaluation Report (ITER), and describes the in situ radio frequency heating (RFH) technology developed by IIT Research Institute (IITRI). For additional information about the SITE Program, this technology, and the demonstration site, key contacts are listed at the end of this section.

1.1 BACKGROUND

A Demonstration Test of IITRI's RFH technology was conducted by the SITE Program in coordination with research efforts sponsored by the U.S. Air Force (USAF). Although the technology was developed by IITRI, Brown and Root Environmental (B&RE) assumed many of the "traditional" responsibilities of the developer during the Demonstration Test. B&RE was hired by USAF to provide an independent evaluation of IITRI's RFH technology, project and site management, design and operation of the vapor collection and treatment systems, and to assist IITRI in the construction and operation of the RFH system. IITRI was subcontracted by B&RE to design and operate the RFH system and the soil vapor extraction (SVE) collection wells.

The SITE demonstration was conducted at Site S-1, located near the northern boundary of Kelly Air Force Base (AFB) near San Antonio, Texas (see Figure 1). This site was used historically as an intermediate storage area for wastes destined for off-base reclamation. The soil is contaminated with mixed solvents, carbon cleaning compounds, and petroleum oils and lubricants. Much of the spilled waste accumulated in a long sausage-shaped "sump," which is the lowest portion of a depression on the eastern side of the site (see Figure 2). The original design treatment zone defined in the Quality Assurance Project Plan (QAPP) was a plot of soil approximately 17.5 feet (5.33 meters) long, 10.0 feet (3.05 meters) wide, and 29.0 feet (8.84 meters) deep. However, due to the presence of shallow groundwater, operational problems experienced during the demonstration, and changes in the original radio frequency (RF) design, the volume of soil to be heated was decreased.

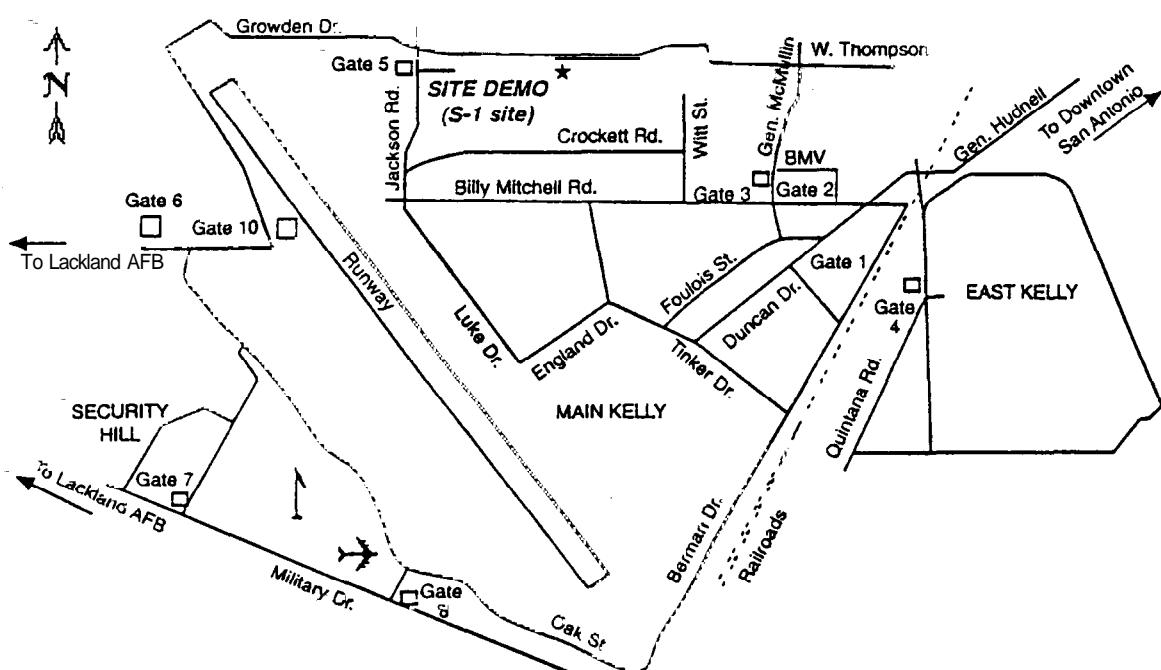
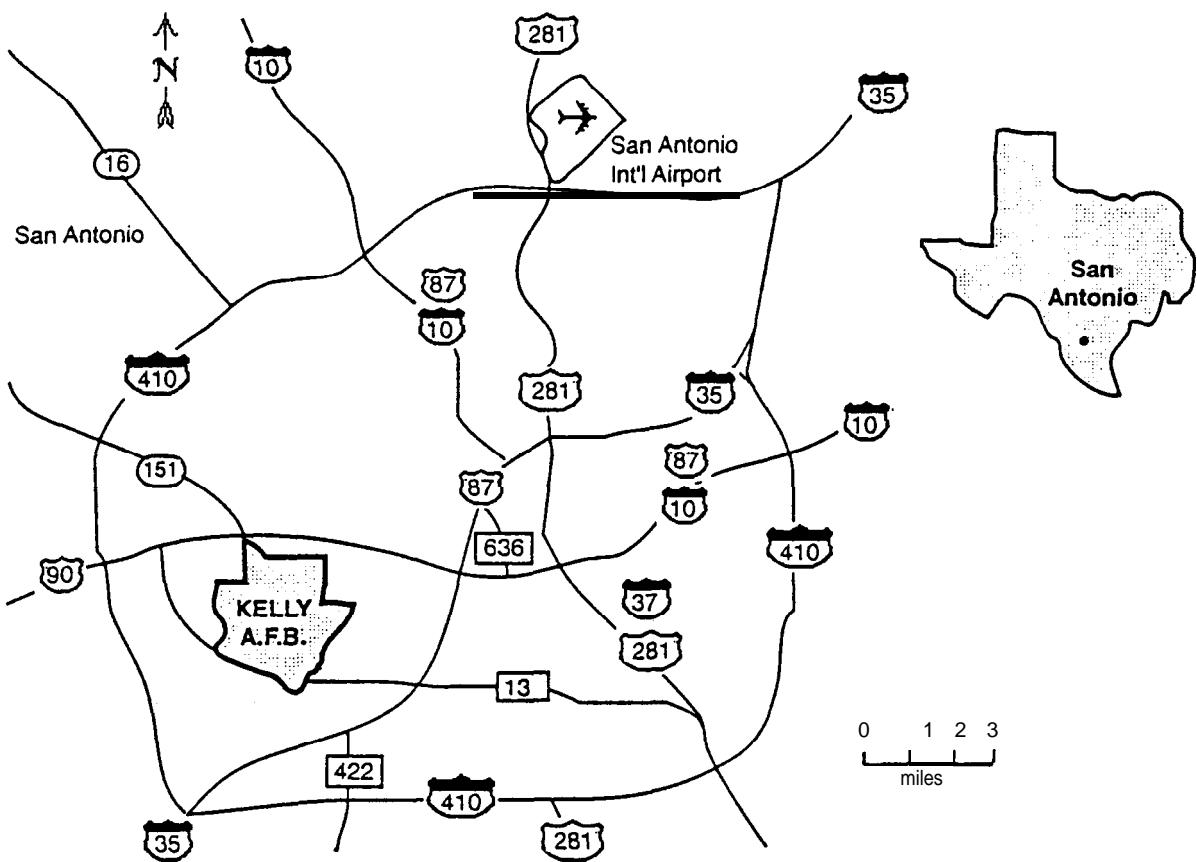


Figure 1. Regional maps showing demonstration location.

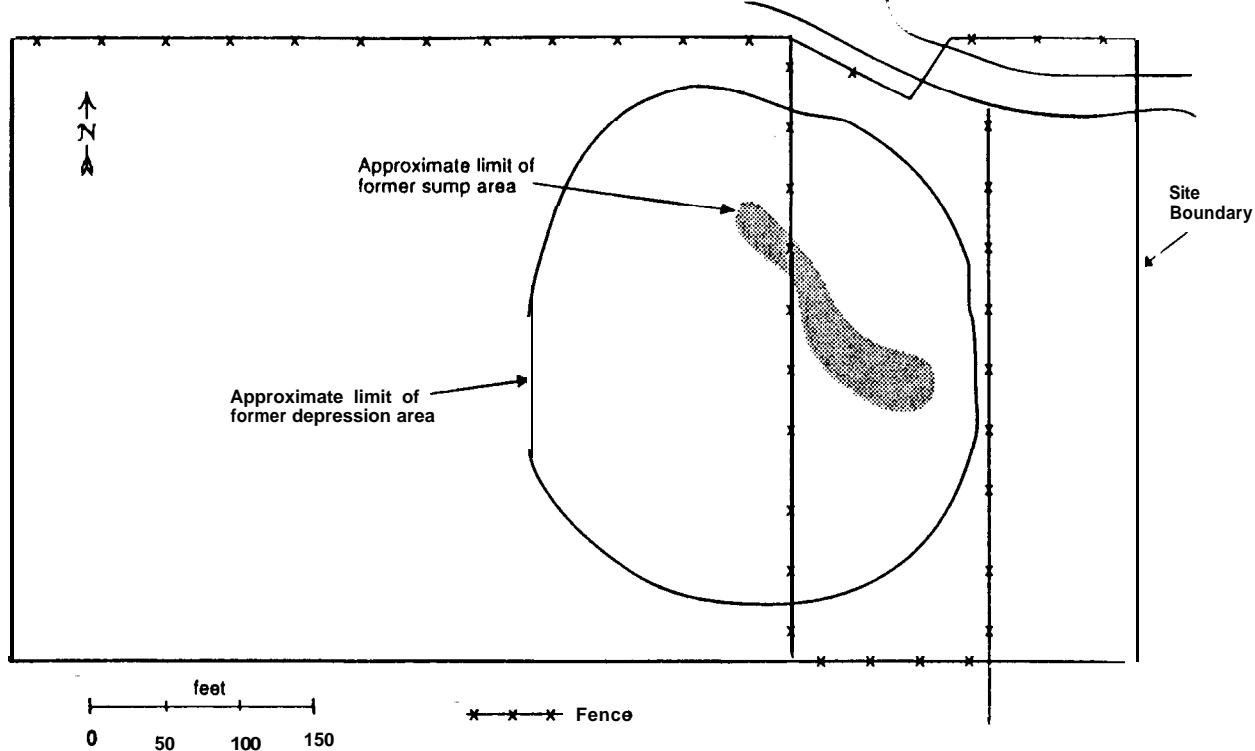


Figure 2. Plan view of the demonstration site.

The bottom ends of the ground and exciter electrodes were placed at depths of 29.0 feet (8.84 meters) and 19.5 feet (5.94 meters) respectively, resulting in an effective heating length of 14.1 feet (4.30 meters) and an effective heating depth of approximately 23.3 feet (7.10 meters) [the width remained at 10 feet (3.05 meters)]. This zone is referred to as the “revised design treatment zone.” It was the intention of the developer to heat the soil and achieve a temperature of 150°C (302°F) throughout the revised design treatment zone, then maintain this temperature for approximately 4 days. However, soil temperature data collected by IITRI indicated a lack of significant heating in remote areas of the revised design treatment zone. The volume of soil in the revised design treatment zone that did achieve this objective is referred to as the “heated zone.” The dimensions of the heated zone are 10.8 feet (3.29 meters) long by 5.7 feet (1.7 meters) wide by 20.0 feet (6.10 meters) deep. Both of these zones are examined in this document. The results of the Demonstration Test and previous tests constitute the basis for this report.

The RFH technology uses electromagnetic energy in the RF band to heat contaminated soil in situ, thereby potentially enhancing the ability of standard SVE technologies to remove volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs) from the soil. Standard alternating

current (AC) electricity is converted to RF energy by an RF generator. The design temperature and duration of heating required are site-specific, depending on the contaminants of concern. The RF energy is conveyed into the soil by exciter electrodes, which extend from the ground surface to the bottom of the treatment zone. As the soil is heated, due to the dissipation of the RF energy, contaminants and moisture in the soil are vaporized. A standard SVE system provides a vacuum to the ground electrodes and transfers the vapors to collection or treatment facilities where noncondensable and condensable vapors are collected for further treatment or disposal. At present, SVE extraction wells are an integral part of IITRI's RFH system, though this may not be the case in the future. A vapor barrier covering the treatment surface area is installed to prevent heat loss, contaminant emission, and air infiltration.

In general, IITRI's RFH system is best suited for treatment of soils composed primarily of sand and other coarse materials. The vendor also claims the technology will work in clay; to substantiate this claim the technology will need to be demonstrated further at other sites containing clay. The clay may also have a low air permeability and impact the operation of the SVE system.

1.2 BRIEF DESCRIPTION OF PROGRAM AND REPORTS

In 1986, the U.S. EPA Office of Solid Waste and Emergency Response (OSWER) and Office of Research and Development (ORD) established the SITE Program to promote the development and use of innovative technologies to clean up Super-fund sites across the country. Now in its ninth year, the SITE Program is helping to provide the treatment technologies necessary to implement new Federal and State cleanup standards aimed at permanent remedies rather than quick fixes. The SITE Program is composed of four major elements: the Demonstration Program, the Emerging Technologies Program, the Measurement and Monitoring Technologies Program, and the Technology Transfer Program.

The major focus has been on the Demonstration Program, which is designed to provide engineering and cost data for selected technologies. To date, the Demonstration Program projects have not involved funding for technology developers. EPA and developers participating in the program share the cost of the demonstration. Developers are responsible for demonstrating their innovative systems at chosen sites, usually Super-fund sites. EPA is responsible for sampling, analyzing, and evaluating all test results. The final product of each demonstration is an assessment of the technology's performance, reliability, and costs. This information is used in conjunction with other data to select the most appropriate technologies for the cleanup of Superfund sites.

Developers of innovative technologies apply to the Demonstration Program by responding to EPA's annual solicitation. EPA also accepts proposals any time a developer has a Super-fund waste treatment project scheduled. To qualify for the program, a new technology must be available as a pilot- or full-scale system and offer some advantage over existing technologies. Mobile technologies are of particular interest to EPA.

Once EPA has accepted a proposal, EPA and the developer work with the EPA regional offices and State agencies to identify a site containing waste suitable for testing the capabilities of the technology. EPA prepares a detailed sampling and analysis plan designed to evaluate the technology thoroughly and to ensure that the resulting data are reliable. The duration of a demonstration varies from a few days to several years, depending on the length of time and quantity of waste needed to assess the technology.

The results of the IITRI RFH technology demonstration are published in two documents: the SITE Technology Capsule and the ITER. The ITER includes information on demonstration costs and performance, implementation problems/limitations, site conditions for which the technology is applicable, waste handling requirements, and an evaluation of the technology in light of the nine criteria used by remedial project managers (RPMs) during the remedial investigation/feasibility study (RI/FS) process. The ITER also describes the demonstration, the developer's experience prior to the demonstration, and the adaptability of the technology. The SITE Technology Capsule is a concise summary of the ITER. Both the SITE Technology Capsule and the ITER are intended for use by RPMs making a detailed evaluation of a technology for a specific site and waste.

The second element of the SITE Program is the Emerging Technologies Program, which fosters the further investigation and development of treatment technologies that are still at the laboratory scale. Successful validation of these technologies can lead to the development of a system ready for field demonstration and participation in the Demonstration Program.

The third component of the SITE Program, the Measurement and Monitoring Technologies Program, provides assistance in the development and demonstration of innovative technologies to characterize Super-fund sites better.

The fourth component of the SITE Program is the Technology Transfer Program, which reports and distributes the results of both Demonstration Program and Emerging Technologies Program studies through ITERs and abbreviated bulletins.

1.3 PURPOSE OF THE ITER

The ITER provides information on the IITRI RFH technology and includes a comprehensive description of the demonstration and its results. The ITER is intended for use by EPA RPMs, EPA on-scene coordinators (OSCs), contractors, and others involved in the remediation decision-making process and in the implementation of specific remedial actions. The ITER is designed to aid decision makers in determining whether specific technologies warrant further consideration as applicable options in particular cleanup operations. To encourage the general use of demonstrated technologies, EPA provides information regarding the applicability of each technology to specific sites and wastes. The ITER includes information on cost and site-specific characteristics. It also discusses advantages, disadvantages, and limitations of the technology.

This report represents a critical step in the development and commercialization of the IITRI RFH technology. The proposed commercial-scale system, which utilizes three 100-kilowatt (kW) units, is described. (Note: total usage of electric or RF power is given in kW-h; therefore, the usage rate is given in kW-h/h, or kW.) The applicability of the proposed system is evaluated. Treatment costs for a full-scale remediation using the 300-kW system are estimated. These costs are presented on a per ton basis to facilitate comparison to other available technologies.

Each SITE demonstration evaluates the performance of a technology in treating a specific waste. The waste characteristics at other sites may differ from the characteristics of those treated during this demonstration. Therefore, successful field demonstration of a technology at one site does not necessarily ensure that it will be applicable at other sites. Data from the field demonstration may require extrapolation to estimate the operating ranges in which the technology will perform satisfactorily. Only limited conclusions can be drawn from a single field demonstration.

1.4 TECHNOLOGY DESCRIPTION

IITRI claims that the RFH technology remediates contaminated soil in situ by heating the soil and volatilizing the contaminants, thus potentially enhancing the performance of standard SVE technologies.

Moisture present in the soil is also volatilized and may provide a steam sweep within the treatment zone, thus further enhancing the removal of organic contaminants. Steam and contaminant vapors are collected by vapor extraction wells and channeled to the vapor treatment system. The vapor treatment system is site- and contaminant-specific and therefore is not included in this evaluation. A basic schematic for the IITRI RFH system used during the SITE demonstration is shown in Figure 3. The relative locations of the subsurface components are shown in Figure 4.

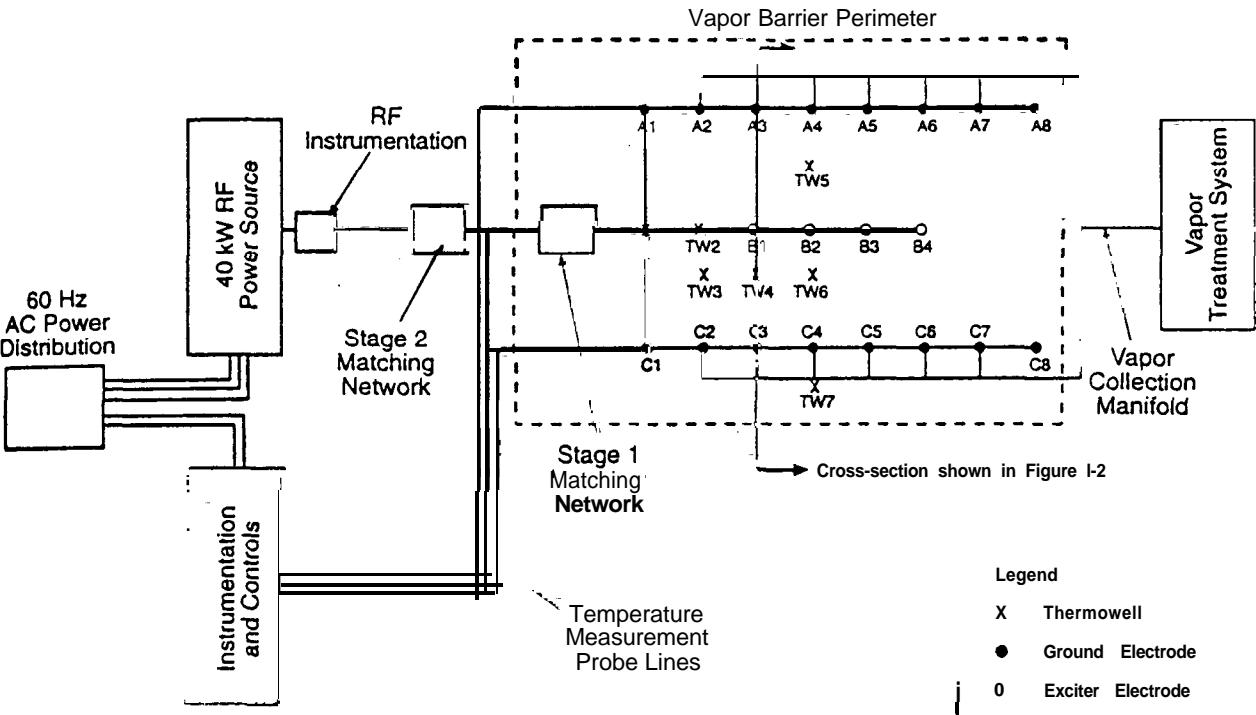


Figure 3. Basic schematic of the IITRI RFH system (not to scale).

The RFH technology is potentially capable of remediating unsaturated soils contaminated with VOCs and SVOCs. RFH is believed to be best suited to the remediation of soils containing a high fraction of sand and other coarse materials. In soils containing a high fraction of silt or clay, contaminants tend to be strongly sorbed to the soil particles. Therefore, removal of the contaminants may become much more difficult since these soils often have insufficient air permeability for adequate removal of vaporized contaminants. The developer claims that the technology is applicable to clayey soils because the permeability of such soils will increase as they dry; this claim needs to be substantiated by conducting further tests with the technology.

A1 A2 A3 A4 A5 A6 A7 A8

▲
TW5

▲ TW1 ▲ TW2 ● B1 ● B2 ● B3 ● B4

▲ TW3 ▲ TW4 ▲ TW6

● C1 ● C2 ● C3 ● C4 ● C5 ● C6 ● C7 ● C8

▲
TW7

0 2.5
Scale in Feet

● Electrode
▲ Thermowell

Figure 4. Relative locations of subsurface components used in the IITRI RFH system.

The components of IITRI's RFH system have two major purposes: transmission of RF energy and collection of vapors. The primary components of the system include the following:

- RF generator — The RF generator converts AC electricity to the desired frequency radio wave. The 40-kW generator used during the SITE demonstration can provide a continuous RF wave at a frequency of 6.78 megahertz (MHz). Operating on a frequency band allocated for industrial, scientific, and medical (ISM) equipment minimizes Federal Communications Commission (FCC) operating requirements. The frequencies allocated for ISM equipment are 6.78 MHz, 13.56 MHz, 27.12 MHz, 40.68 MHz, and seven higher frequencies.

- Matching network – RF energy from the generator flows to the matching network, which is used to adjust the electrical characteristics of the RF energy being transmitted into the soil. Continuous monitoring and adjustment are required because the dielectric characteristics of the soil change as it is heated. The matching network allows the RFH system to compensate for these changes. Proper operation of the matching network maximizes the fraction of the power from the RF generator that is absorbed by the soil. This is important for two reasons. First, the higher the fraction of power absorbed by the soil, the more energy-efficient the system. Second, power that is not absorbed by the soil is reflected back to the generator and other electrical components. Excessive reflected power will cause the electrical components to overheat.
- Exciter electrodes – Energy from the RF generator flows through the matching network and coaxial cables and onto the exciter electrodes, which convey the energy into the soil. The exciter electrodes extend vertically from just above the ground surface to near the bottom of the treatment zone. The exciter electrodes used during the SITE demonstration were fabricated from 2.5-inch (0.064 meters) and 4-inch (0.10 meters) copper pipe and were installed in 10-inch (0.25 meters) boreholes to a depth of 19.5 feet (5.94 meters) below the surface. The boreholes were backfilled around the electrodes using a material similar to the surrounding soil. The revised design treatment zone contained one row of four exciter electrodes spaced 2.5 feet (0.76 meters) apart (see Figures 3 and 4).
- Ground electrodes – Two rows of eight ground electrodes each were installed parallel to and on either side of the exciter electrode row. The ground electrodes were fabricated from 2-inch (0.05meter) diameter aluminum pipe and were 29 feet (8.8 meters) in length. The electrode configuration was designed to direct the flow of RF energy through the soil and contain the energy within the treatment zone. The outer casing of the ground electrodes was perforated on the side facing the treatment zone to permit the collection of vapors from the soil. They were perforated in a uniform pattern over the full length of the electrode with the exception of the four corner electrodes, which were not perforated. Each perforated ground electrode was connected to a manifold, which led to the vapor treatment system. Two additional perforated vapor extraction pipes were installed parallel to the ground surface to prevent buildup of vapors below the vapor barrier.
- Thermowells – Thermowells are Teflon@ tubes sealed at the bottom with approximately 1 to 2 inches (0.03 to 0.05 meters) of silicon oil in their bottoms. Each thermowell was designed to hold either six thermocouples or one fiber optic probe. The SITE demonstration used seven thermowells.
- Fiber optic probes – Fiber optic probes were inserted into those thermowells that were between the two ground electrode rows (Thermowells 1 through 6). The probes went all the way to the bottoms of the thermowells and contained four tips each to take four temperature readings.. Readings were taken every 24 hours and could be taken with the RF power on. Toward the end of the project, the excessive heat caused several tips of the fiber optic probes to break off; all were replaced with thermocouples.
- Thermocouples – The temperature of the soil is monitored by thermocouples positioned throughout the treatment zone. During the SITE demonstration, the thermocouples were placed in the thermowells and on the inner walls of the ground or exciter electrodes.

Thermocouples were located at depths of 1, 12, 24, and 29 feet (0.3, 3.7, 7.3, and 8.8 meters) on the inner walls of the ground electrodes. On the exciter electrodes, thermocouples were located at depths of 1, 10, and 19 feet (0.3, 3.0, and 5.8 meters). Thermocouples were also located at depths of 1, 12, 24, 29, 31, and 34 feet (0.3, 3.7, 7.3, 8.8, 9.4, and 10 meters) in Thermowell 7 at the start of the demonstration. Due to the malfunction of the fiber optic probes previously explained, thermocouples were used in Thermowells 1 through 6 at the end of the demonstration.

- Aboveground vapor collection pipes – These perforated pipes collect any vapors that rise to the surface of the treatment zone.
- Vapor collection manifold – The ground electrodes and the aboveground vapor collection pipes feed the manifold, which gathers the vapors together and channels them into the vapor treatment system.
- Blower – The blower provides a vacuum throughout the treatment zone by pulling the contaminated air stream through the vapor collection manifold and vapor collection pipes.
- Vapor barrier – The vapor barrier is fabricated from three layers of material: a fiberglass-reinforced silicone sheet; a 3-inch (0.08-meter) thick layer of fiberglass insulation; and a polyethylene (or other plastic) sheet. The heat-resistant silicone sheet is the layer nearest to the ground surface. This layer prevents the release of volatilized contaminants, helps maintain a vacuum in the treatment zone, and protects one side of the insulation. The layer of insulation reduces heat loss from the treatment zone. The top sheet of plastic protects the other side of the insulation and prevents infiltration of air into the treatment zone.
- RF shield – A corrugated aluminum arch with flat aluminum ends (shown in Figure 5) covers the same area as the vapor barrier and serves as an RF shield. It is designed to limit the amount of RF energy that escapes the system. A weather cover, designed to be airtight, protects the RF shield.

Extended ground Plane – An extended ground plane made of wire cloth connects the RF shield to the ground electrodes. The extended ground plane helps contain the RF energy within the treatment zone.

Expanded metal shield – An expanded metal shield lies on top of the vapor barrier and extends 10 feet (3.0 meters) beyond each side of the treatment zone. The expanded metal shield helps contain the RF energy within the treatment zone, minimizes or prevents interference from radio broadcasts, and provides a safe working environment for the workers.

Although not a component of IITRI's RFH technology, the vapor treatment system is crucial to the overall process. During the SITE demonstration, vapors which condensed in the vapor collection system piping were collected as liquids. The uncondensed portion of the vapor stream was incinerated in a propane-fueled flare. Other sites may require more complex vapor treatment systems. Groundwater

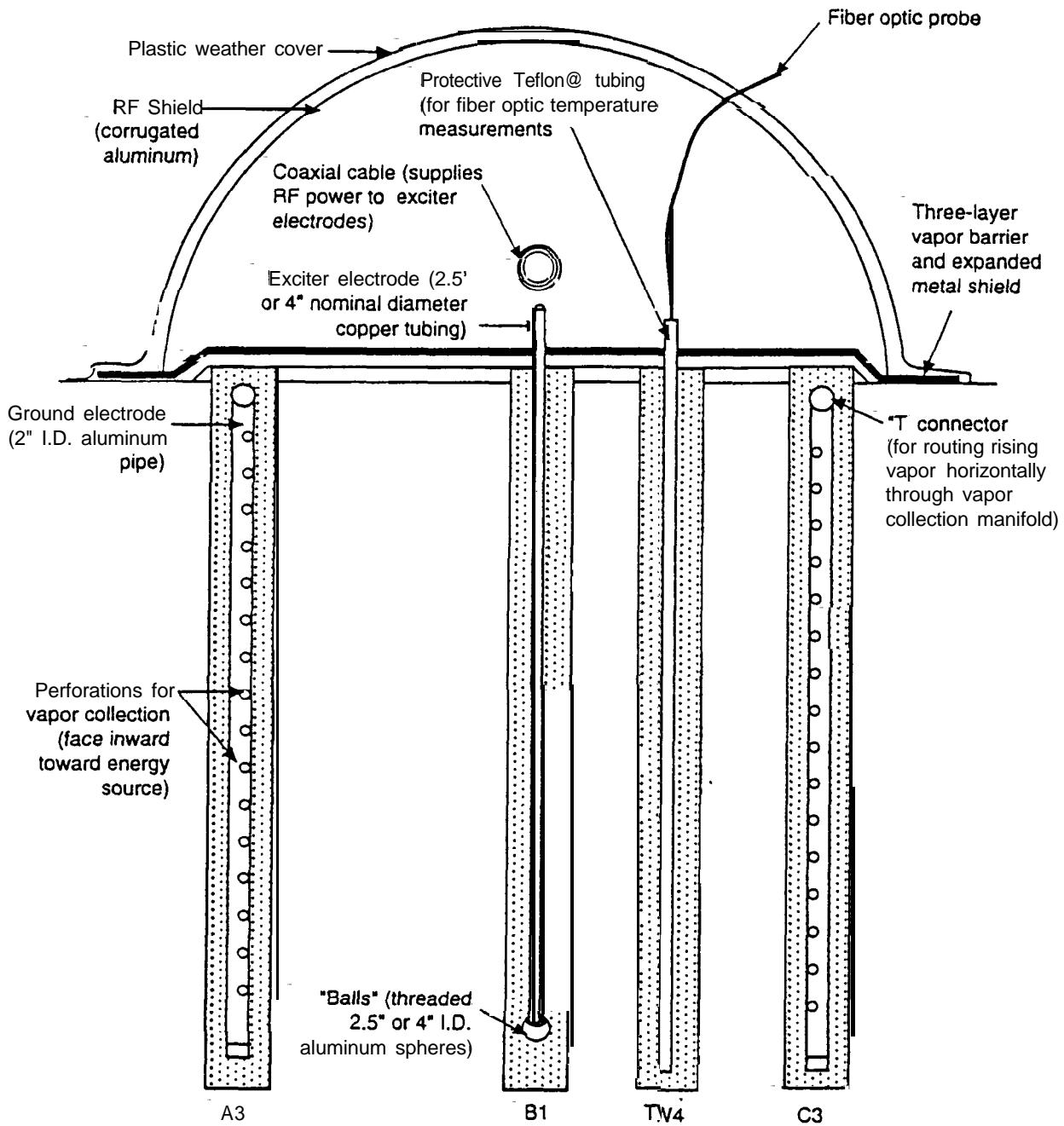


Figure 5. Cross-section of II TRI's RFH system (not to scale).

treatment or disposal is also not directly related to the RFH process but must be considered when deciding to implement the RFH technology at a site. Groundwater that is present at a site will have to be removed from the RFH treatment area using groundwater dewatering wells prior to implementation of the RFH technology. Groundwater from dewatering wells will likely require analysis in order to determine if it requires treatment or can simply be disposed of.

The RFH system is transported to the site in trailers. The generator and instrumentation remain in trailers throughout treatment. The onsite assembly of the RFH system begins with the installation of the electrodes and thermowells. Each ground or exciter electrode is installed by drilling a hole to the required depth, inserting the electrode into the borehole, and backfilling the hole with material similar to the soil at the site. Thermowells are installed in the same way, except that a piece of polyvinyl chloride (PVC) pipe is used to guide the thermowell into the borehole. The PVC pipe is removed from the borehole before the hole is backfilled. The developer claims it may be possible to spread soil cuttings from the boreholes uniformly over the treatment zone and compact and treat them with the undisturbed soil. Alternatively, the cuttings can be drummed and transported offsite for treatment or disposal as was done during the SITE demonstration.

Installation of aboveground components can be conducted during the installation of the subsurface components. After all aboveground and subsurface components are installed and the piping and wiring between the electrodes and thermocouples are completed, the exciter electrodes are connected to the matching network, RF generator, and RF instrumentation. The thermocouples are connected to monitoring instruments. The ground electrodes are also part of the vapor collection system, which is piped to the vapor treatment system.

After installation and assembly, shakedown and testing of the system are necessary. The system is tested and any necessary adjustments are made. If desired, the SVE system may be operated before heat is applied to the soil. The SVE system continues to operate as the RF system is activated and heat is applied to the soil. Treatment continues until the termination criteria are met. The termination criteria are extremely site-specific and are established prior to the remediation effort. The criteria are based on results from treatability studies, site characterizations, and cleanup levels. Termination criteria may include the following:

- The average soil temperature in the treatment zone has been maintained at the desired temperature for the desired amount of time.
- Contaminant concentrations in the vapor stream have dropped to concentrations below levels established in the project objectives.
- It becomes difficult to deliver sufficient RF energy efficiently into the treatment area to maintain the average soil temperature above a preset level.

The termination criteria may require adjustment based on information collected during treatment. During the SITE demonstration, heat was applied to the revised design treatment zone for 9 weeks.

After treatment is complete, the treatment zone must be allowed to cool. If the treatment zone did not encompass all of the contaminated soil at the site, the aboveground components of the RFH system can be disassembled, moved to another portion of the site, and reassembled while the treated soil cools. If the commercial-scale system includes two sets of subsurface components, treatment of a second treatment zone can begin while the first zone is cooling.

During the SITE demonstration, which was conducted during the summer in San Antonio, Texas, the soil was allowed to cool for 2 months prior to post-treatment sampling after reaching temperatures 1,300°C (2372°F) and higher near the exciter electrodes. It is possible that the cooldown period of a zone at another site may be shorter in duration than the cooldown period in the SITE demonstration. An alteration of the RF design may provide more uniform heating throughout the treatment zone and thus prevent what occurred during the SITE demonstration – some areas of the revised design treatment zone achieved temperatures much higher than the desired treatment temperature while, at the same time, other areas did not reach the desired treatment temperature.

After the treatment zone cools, post-treatment soil samples are collected to determine the extent of treatment. All subsurface components are removed through the use of a drill rig. The boreholes are then generally backfilled with bentonite, as was done at this site.

1.5 KEY CONTACTS

For more information on the demonstration of the in situ IITRI RFH technology, please contact:

1. EPA Project Manager for the SITE Demonstration Test:

Laurel Staley
U.S. Environmental Protection Agency
Risk Reduction Engineering Laboratory
26 West Martin Luther King Drive
Cincinnati, Ohio 45268
(513) 569-7863

2. Process Vendor:

Harsh Dev
IIT Research Institute
10 West 35th Street
Chicago, Illinois 60616
(312) 567-4257

3. Kelly AFB Project Engineer for Site S-1 RFH Field Demonstration:
Victoria Wark
SA-ALC/EMRO
305 Tinker Drive, Suite 2, Building 305
Kelly AFB, TX 78241-5915
(210) 925-1812
4. B&RE Project Manager:
Clifton Blanchard
800 Oak Ridge Turnpike, Suite A.600
Oak Ridge, TN 37830
(615) 483-9900
5. USAF Technical Program Manager, Site Remediation Division:
Paul F. Carpenter
AL/EQW-OL
139 Barnes Drive, Suite 2
Tyndall AFB, FL 32403
(904) 283-6187

Information on the SITE Program is also available through the following online information clearinghouses:

- The Alternative Treatment Technology Information Center (ATTIC) is a comprehensive, automated information retrieval system that integrates data on hazardous waste treatment technologies into a centralized, searchable source. This data base provides summarized information on innovative treatment technologies. The system operator can be reached at (703) 908-2137. The ATTIC System access number is (703) 908-2138.

The Vendor Information System for Innovative Treatment Technologies (VISITT) data base contains information on 154 technologies offered by 97 developers: (800) 245-4505.

The OSWER cleanup information (CLU-IN) electronic bulletin board contains information on the status of SITE technology demonstrations. The system operator can be reached at (301) 589-8268. The system access number is (301) 589-8366.

Technical reports can be obtained by contacting the Center for Environmental Research Information (CERI), 26 West Martin Luther King Drive, Cincinnati, Ohio 45268 at (513) 569-7562.

SECTION 2

TECHNOLOGY APPLICATIONS ANALYSIS

This section provides information on the ability of IITRI's RFH system to meet regulatory and operational requirements associated with the remediation of Superfund sites. It includes a discussion on how use of this technology will satisfy the applicable or relevant and appropriate requirements (ARARs) for Superfund site remediations. Also included in this section is information on the operability, applicability, key features, availability and transportability, material handling requirements, site support requirements, and limitations of IITRI's RFH technology.

2.1 OBJECTIVES: PERFORMANCE VERSUS ARARs

ARARs consist of Federal, State, and local regulatory requirements that must be considered when remediating Superfund sites. These requirements include seven major Federal statutes discussed in the subsequent subsections. Each statute can have corresponding State or local laws that are more stringent than the Federal counterparts. Table 2 lists ARARs that should be considered when using the IITRI RFH System at a Superfund site.

2.1.1 Comprehensive Environmental Response, Compensation, and Liability Act

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), as amended by the Superfund Amendments and Reauthorization Act (SARA) of 1986, provides for Federal funding to respond to releases of hazardous substances to air, water, and land. Section 121 of SARA, Cleanup Standards, states a strong statutory preference for remedies that are highly reliable and provide long-term protection. It strongly recommends that remedial actions use onsite treatments that " . . . permanently and significantly reduce the volume, toxicity, or mobility of hazardous substances." Nine general criteria that must be addressed by CERCLA remedial actions are listed in Table 1 in the Executive Summary.

Table 2. Potential Federal and State ARARs for the Treatment of Contaminated Soil by the IITRI RFH System at a Superfund Site

Process Activity	ARAR	Description	Basis	Response
Storage prior to processing	RCRA ¹ 40 CFR ² Part 26 I or State equivalent	Identification and characterization of the soil to be treated.	A requirement of RCRA prior to managing the waste.	Chemical and physical analyses must be performed
	TSCA ³ 40 CFR Part 761 or State equivalent	Standards that apply to the treatment and disposal of wastes containing PCBs.	During waste characterization, PCBs may be identified in the waste and, if present above regulatory thresholds (50 ppm for TSCA), the waste is subject to TSCA regulations.	Analysis for PCBs must be performed if potentially present.
Waste processing	<90 days: RCRA 40 CFR Part 262 or State equivalent	Standards applicable to the storage of hazardous waste in containers or tanks	Contaminated groundwater extracted by dewatering wells and soil cuttings from boreholes meeting the definition of hazardous waste must meet substantive requirements of RCRA storage regulations.	Ensure storage containers and tanks are in good condition, provide secondary containment, where applicable, and conduct regular inspections.
	> 90 days: RCRA 40 CFR Part 264 or State equivalent			
Storage and disposal after processing	RCRA 40 CFR Part 264 or State equivalent	Standards applicable to the treatment of hazardous waste at permitted facilities.	Treatment of hazardous waste must be conducted in a manner that meets the substantive requirements of a RCRA Part B permit.	Equipment must be operated, maintained, and monitored properly.
	CAA ⁴ 40 CFR or State equivalent	Standards applicable to emissions from treatment equipment.	Air emissions may have to be controlled to meet the substantive requirements of CAA permit.	Emission control devices may need to be installed to treat air emissions from the SVE unit.
waste characterization (treated waste and residuals)	RCRA 40 CFR Parts 264 and 268 or State equivalents	Standards that apply to the storage of hazardous waste in containers or tanks and the disposal of hazardous wastes in surface impoundments, landfills, and other land structures.	Contaminated groundwater extracted by dewatering wells, condensate, spent carbon (if used), and soil cuttings meeting the definition of hazardous waste must meet substantive requirements of RCRA storage regulations and must not be land disposed without meeting specific treatment requirements.	The contaminated groundwater, condensate, and soil cuttings meeting the definition of hazardous waste must be stored in containers or tanks that are well maintained and must not be land disposed without meeting all applicable treatment requirements.
	TSCA 40 CFR Part 761.65	Standards that apply to storage of wastes containing PCBs.	Groundwater, condensate, spent carbon (if used), and soil cuttings may contain PCBs above regulatory thresholds.	Ensure disposal of TSCA-regulated waste within 1 year of placement into storage.
	RCRA 40 CFR Part 261 or State equivalent	Identification and characterization of in situ soil, soil cuttings, spent carbon (if used), groundwater, and condensate.	A requirement of RCRA prior to managing the waste necessary to determine regulatory status of in situ soil.	Chemical and physical tests must be performed on the in situ soil, groundwater, soil cuttings, and condensate.
	TSCA 40 CFR Part 761 or State equivalent	Standards that apply to the treatment and disposal of wastes containing PCBs.	Soil cuttings, spent carbon (if used), and condensate may contain PCBs above regulatory thresholds.	Analysis for PCBs must be performed if PCBs were present in untreated soil.

Table 2. Potential Federal and State ARARs for the Treatment of Contaminated Soil by the IITRI RFH System at a Superfund Site (Continued)

Process Activity	ARAR	Description	Basis	Response
Transportation for offsite disposal	RCRA 40 CFR Part 262 or State equivalent	Manifesting, packaging, and labeling requirements prior to transporting.	The contaminated groundwater, condensate, and soil cuttings may need to be manifested and managed as a hazardous waste.	An identification (ID) number must be obtained from EPA.
	RCRA 40 CFR Part 263 or State equivalent	Packaging, labeling, and transportation standards.	Transportation of hazardous waste must be licensed by EPA and meet specific requirements	A licensed hazardous waste transporter must be used to transport the hazardous waste.
	DOT ⁵ 49 CFR		Hazardous materials must meet specific packaging and labeling requirements.	Shipments of material must be properly containerized and labeled.
Groundwater and condensate discharge	CWA ⁶ 40 CFR Parts 122, 301,304,306, 307,308, and 401-471.	Standards that apply to discharge of contaminated water into sewage treatment plants or surface water bodies.	The groundwater and condensate may not meet local pretreatment standards without further treatment or may require a NPDES permit for discharge to surface water bodies.	Determine if the groundwater and condensate could be discharged to a sewage treatment plant or surface water body without further treatment. If not, the water may need to be further treated to meet discharge requirements.
	SDWA ⁷ 40 CFR Parts 144 and 145	Standards that apply to the disposal of contaminated water in underground injection wells (including infiltration galleries).	Injection of the groundwater and condensate may be the preferred option for management of water from treatment at remote sites.	If underground injection is selected as a disposal means for treated water, testing must be performed and permission must be obtained from EPA to use existing permitted underground injection wells or to construct and operate new wells.
Worker activities throughout the remediation	OSHA ⁹ 29 CFR 1910	Training and protection requirements for workers at hazardous waste sites.	Workers must complete training prior to performing duties.	Ensure workers have completed mandatory training and have appropriate safety equipment

RCRA is the Resource Conservation and Recovery Act.

CFR is the Code of Federal Regulations

TSCA is the Toxic Substances Control Act.

CAA is the Clean Air Act.

DOT is Department of Transportation.

CWA is the Clean Water Act.

SDWA is the Safe Drinking Water Act.

CERCLA is the Comprehensive Environmental Response, Compensation, and Liability Act

OSHA is the Occupational Safety and Health Administration.

2.1.2 Resource Conservation and Recovery Act

The Resource Conservation and Recovery Act (RCRA) is the primary Federal legislation governing hazardous waste activities. Subtitle C of RCRA contains requirements for generation, transport, treatment, storage, and disposal of hazardous waste. Compliance with these requirements is mandatory for CERCLA sites generating, storing, treating, or disposing of hazardous waste onsite.

Treatment, storage, or disposal of hazardous waste typically requires the issuance of a RCRA Part B treatment, storage, or disposal (TSD) permit. At Superfund sites, the onsite treatment, storage, or disposal of hazardous waste must meet the substantive requirements of a TSD permit. RCRA administrative requirements such as reporting and recordkeeping, however, are not applicable for onsite actions.

A Uniform Hazardous Waste Manifest, or its State counterpart, must accompany offsite shipment of hazardous waste, and transport must comply with Federal Department of Transportation (DOT) hazardous waste packaging, labeling, and transportation regulations. The receiving TSD facility must be permitted and in compliance with RCRA standards.

The RCRA land disposal restrictions (LDRs) in 40 CFR 268 preclude the land disposal of hazardous waste that fails to meet stipulated technology or treatment standards. In situ treatment of media contaminated with hazardous waste does not trigger LDRs for the soil or groundwater remaining in place. Consequently, soil that is treated in situ by the IITRI RFH system does not have to meet LDRs but may have to meet other criteria in order to remain in place. Soil or groundwater that is removed and treated must meet LDRs prior to placement back onto the ground. For groundwater, this requirement means that treatment must reduce the contaminants that make the water hazardous, and all other LDR-triggering contaminants, to levels specified in 40 CFR 268 before the treated water can be land disposed (e.g., reintroduced into the ground via an infiltration gallery). The technology or treatment standards applicable to the residuals produced by the IITRI RFH system are determined by the type and characteristics of the hazardous waste present in the soil being remediated. In some cases, variances from LDRs can be obtained from EPA.

2.1.3 Clean Air Act

The Clean Air Act (CAA) establishes primary and secondary ambient air quality standards for the protection of public health and emission limitations for six criteria air pollutants designated by the EPA. Requirements under the CAA are administered by each state as part of the State Implementation Plans developed to bring each state into compliance with the National Ambient Air Quality Standards (NAAQS). The ambient air quality standards listed for specific pollutants may be applicable to operation of the IITRI RFH system due to potential air emissions. A vapor barrier and vapor collection system are designed to prevent the release of the contaminants to the air.

The vapor treatment system must be designed in compliance with the CAA and evaluated on a site-specific basis. The vapor treatment system employed during the SITE demonstration consisted of condensate collection and a propane-fueled flare. According to B&RE, the flare operated under Standard Exemption Number 68 as defined in Section 382.057 of the Texas Clean Air Act.

2.1.4 Safe Drinking Water Act

The Safe Drinking Water Act (SDWA) establishes primary and secondary national drinking water standards. CERCLA refers to these standards, and Section 121(d)(2) explicitly mentions two of these standards for surface water or groundwater: Maximum Contaminant Levels (MCLs) and Federal Water Quality Criteria. Alternate Concentration Limits may be used when conditions of Section 121 (d)(2)(B) are met and cleanup to MCLs or other protective levels is not practicable. Included in these sections is guidance on how these requirements may be applied to Superfund remedial actions. The guidance, which is based on Federal requirements and policies, may be superseded by more stringent promulgated State requirements, resulting in the application of even stricter standards than those specified in Federal regulations. If it is desired to inject the groundwater extracted by dewatering wells, condensate from the vapor collection system, and water generated from decontamination procedures into the ground (as when an infiltration gallery is used), compliance with SDWA and State regulations is required.

2.1.5 Clean Water Act

The Clean Water Act (CWA) regulates direct discharges to surface water through the National Pollutant Discharge Elimination System (NPDES) regulations. These regulations require point-source discharges of wastewater to meet established water quality standards. The discharge of wastewater to a sanitary sewer requires prior approval from State and local regulatory authorities that the wastewater is

in compliance with applicable pretreatment standards.

Depending on the applicable CWA regulations and site conditions, the extracted groundwater and condensate may have to be further treated prior to discharge. Discharge to a publicly-owned treatment works (POTW) will typically be regulated according to the industrial wastewater pretreatment standards of the POTW. These standards are specified in 40 CFR 401-471 for certain industries. Depending on the type of site, the treated water may fall into one of the specific industrial categories. If it does not, the pretreatment standards for the treated water are determined by the POTW and depend on site-specific parameters such as the flow rate to the POTW, the contaminants present, and the design of the POTW.

If pollutants are present in the groundwater and condensate, discharge to a surface water body must meet the substantive requirements of an NPDES permit effluent and be in compliance with the provisions of 40 CFR 122, et seq. In order to meet either NPDES discharge limits or POTW pretreatment standards, treatment of the groundwater and condensate may be required.

2.1.6 Toxic Substances Control Act

The Toxic Substances Control Act (TSCA) grants EPA the authority to prohibit or control the manufacturing, importing, processing, use, and disposal of any chemical substance that presents an unreasonable risk of injury to human health or the environment. These regulations are found in 40 CFR 761. With respect to waste regulation, TSCA focuses on the use, management, disposal, and cleanup of polychlorinated biphenyls (PCBs). Materials with less than 50 parts per million (ppm) PCBs are classified as non-PCB, those with PCB concentrations between 50 and 500 ppm are classified as PCB-contaminated, and those with PCB concentrations greater than or equal to 500 ppm are classified as PCBs. State PCB regulations may be more stringent than TSCA regulations. PCBs were not anticipated to be present at the Demonstration Test site and therefore, no analysis was performed.

2.1.7 Occupational Safety and Health Administration Requirements

The Occupational Safety and Health Administration (OSHA) requires personnel employed in hazardous waste operations to receive training and comply with specified working procedures while at hazardous sites. These regulations (29 CFR 1910) stipulate that workers must receive appropriate training to recognize hazardous working conditions and to protect themselves adequately from those conditions. This training typically includes a 24- or 40-hour course and an annual 8-hour refresher class.

Proper personal protective equipment (PPE) should be available and properly utilized by all onsite personnel. At each site, the level of PPE required is determined based on the potential hazards associated with the site and the work activities being conducted.

OSHA has provided guidance, published in 20 CFR Part 1910.97, for exposure to electromagnetic radiation in the RF region. This guidance states that “for normal environmental conditions and for incident electromagnetic energy of frequencies from 10 MHz to 100 gigahertz (GHz), the radiation protection guide is 10 mW/cm² for periods of 0.1 hour or more, or an energy density of 1 mW-hr/cm² during any 0.1 hour period”. OSHA recommends that exposure should not exceed the limits of the guidance without careful consideration.

2.2 OPERABILITY OF THE TECHNOLOGY

IITRI’s RFH system is described in detail in Subsection 1.4. The components of the system have two major purposes: (1) to heat the soil by transmitting RF energy into it and (2) to collect the vapors released by the heated soil. During the SITE demonstration, IITRI was subcontracted by B&RE to design and operate all of the RFH system except the vapor treatment system. B&RE provided project and site management, operated the vapor treatment system, and assisted IITRI in the construction and operation of the RFH system.

Two significant operational problems were encountered during the demonstration. IITRI had planned to use a new 50-kW RF generator for the demonstration. However, the unit did not perform correctly during startup and was replaced with a 40-kW generator that had been used during earlier tests. This change did not appear to affect the amount of soil treated. Also, exciter electrodes removed after the demonstration had melted, providing evidence of a system malfunction that prevented full utilization of RF power for soil heating. The developer believes that the shallow groundwater table contributed to the meltdown. Because a dewatering system was installed and operated by B&RE to prevent this type of problem, it appears that either the dewatering system was inadequate or IITRI underestimated the distance that must be maintained between the groundwater and the bottom ends of the exciter electrodes.

Several operating parameters affect the performance of the RFH system. The treatment temperature determines the rate at which contaminants are volatilized as well as the range of contaminants that will be volatilized. The length of time the treatment temperature is maintained influences the final contaminant concentrations. Operating temperature and treatment time are typically selected based on the contaminants of concern, required cleanup levels, and soil characteristics. The soil at Site S-1, where the SITE demonstration was conducted, is contaminated with mixed solvents, carbon cleaning compounds, and petroleum oils and lubricants. The contaminants of concern were VOCs and SVOCs. It was the goal of the developer to achieve a soil temperature of 150°C (302°F) in the revised design treatment zone, then maintain this temperature for approximately 4 days. Due to limited communication between the developer and the SITE Program, the Demonstration Plan states that the goal was to maintain a soil temperature of 150°C (302°F) for 2 weeks.

Because much of the revised design treatment zone never reached 150°C (302°F), it is not possible to calculate a length of time for which the zone was maintained at the treatment temperature. Temperature monitoring results are presented in greater detail in Appendix A. The area within the revised design treatment zone that achieved a temperature of greater than 150°C (302°F) and maintained that temperature for at least 2 weeks is referred to as the heated zone (a duration of 2 weeks is used to maintain agreement with the Demonstration Plan).

The design and operation of the vapor collection system are crucial to the performance of the RFH technology. Factors that can be varied include the number and design of the vapor collection pipes, the location (configuration) of the vapor collection pipes within the treatment zone, the amount of vacuum applied to the vapor collection system, and the amount of time the vapor collection system is operated.

Analysis of the SVE design used during the SITE demonstration revealed several problems which negatively impacted the ability of the RF technology to remove the contaminants in the revised design treatment zone. Two-dimensional modeling of gas flow rates was used to evaluate inward migration and treatment zone extraction rates qualitatively. The results of this modeling indicate inward gas flows. Due to inefficiencies in the design of the SVE system, gas flows between the outer edge of the impermeable cap and the extraction wells were five times greater than those between the two rows of extraction wells. As a result, contaminant migration into the treatment zone was possible, especially near the outer edges, and contaminant removal from the treatment zone may have been slow compared to inward contaminant migration.

Another problem with the SVE design was that the ground electrodes, also serving as the vacuum wells, were connected to the same blower by a manifold and were operated at the same vacuum. The vacuum wells created a significant vacuum under the vapor barrier, and air was drawn laterally under the edges of the vapor barrier to the vacuum wells. However, there was a rather large domain bordered by the two rows of ground electrodes and topped by the vapor barrier in which the gas pressure gradient was extremely small. The soil gas velocity in this stagnation region was therefore very small, so SVE was very slow and inefficient in this region; this region constituted a major part of the revised design treatment zone.

The design of the SVE system must be altered in order to evaluate the effectiveness of the RF technology properly. Extraction wells closer to the center of the domain of interest and installation of passive vent wells may improve the SVE system. A set of passive vent wells, screened along their entire lengths, could be placed around the perimeter of the domain of interest. This would serve to prevent the flow of air into the domain of interest from the surrounding soil, since it eliminates all air pressure gradients in the soil immediately surrounding the domain of interest.

As was the case during the SITE demonstration, the presence of shallow groundwater can greatly impede the heating process and increase costs due to the need to install dewatering wells and/or subsurface hydraulic barriers.

2.3 APPLICABLE WASTES

The RFH technology is potentially capable of remediating soils contaminated with VOCs and SVOCs. Contaminants that can potentially be removed from the soil include: halogenated and nonhalogenated solvents; straight-chain and polycyclic aromatic hydrocarbons found in gasoline, jet fuel, and diesel fuel; and other VOCs and SVOCs. During a test conducted at Volk Air National Guard Base (ANGB), IITRI's RFH system effectively removed both VOCs and SVOCs from homogenous sandy soil [1]. Tests performed in the heterogeneous soils present at Kelly AFB and Rocky Mountain Arsenal (RMA) produced less positive results [2]. These tests are briefly described in Appendix B.

In general, IITRI's RFH system is best suited for treatment of soils composed primarily of sand and other coarse materials. The developer claims the technology will also remove contaminants in a clay medium. However, conducting further tests of the technology in clay is recommended before this claim

can be substantiated. Soils containing a large fraction of clay may have low air permeability and impact the operation of the SVE system. IITRI claims that the air permeability of clayey soils is enhanced as these soils dry. Clay soils often shrink and crack as they dry causing secondary porosity. Air permeability may be increased in the process, but this does not ensure adequate contaminant removal. The technology is also applicable to unsaturated soils regardless of moisture content. Theoretically, RF energy preferentially heats moisture in the soil, causing it to act as a steam sweep to further enhance the removal of organic contaminants. As a result, moist soils can provide improved absorption of the RF energy but generally require additional energy, particularly if the target soil temperature is above the boiling point of water. The dielectric constant of the soil determines the soil's ability to absorb RF energy directly.

2.4 KEY FEATURES OF THE IITRI RFH TECHNOLOGY.

IITRI's RFH technology is similar to both in situ SVE and in situ steam extraction. In SVE, vacuum blowers induce air flow through the soil, stripping VOCs and SVOCs from it [3]. In steam extraction, steam is injected into the soil to raise the soil temperature and strip VOCs and SVOCs from it [4]. The primary difference between these technologies and RFH is that RFH uses RF energy to heat the soil in the treatment zone. Because the RFH technology uses higher temperatures, it is more aggressive than either steam extraction or SVE. Theoretically, RFH should therefore be applicable to less volatile contaminants as well as VOCs.

2.5 AVAILABILITY AND TRANSPORTABILITY OF SYSTEM

IITRI owns and operates one 40-kW RFH system, which was used for the SITE demonstration. The assembly of this system is a multi-step process. The system is transported in two semitrailers; the instrumentation is housed in one trailer, and the RF power source in the other. Each of the trailers has extra space for transportation of the remaining system components. Access roads are required for equipment transport. The assembly of the proposed 300-kW (three 100-kW units) RFH system will be similar to the assembly of the existing 40-kW system. It is projected that the 300-kW system will be transported on four trailers. A full-scale system will use more electrodes and thermowells than the pilot-scale system, but the multi-step installation process will be the same.

2.6 MATERIALS HANDLING REQUIREMENTS

Materials handling requirements prior to treatment are minimal because this is an in situ system. IITRI claims it may be possible to place soil cuttings removed from boreholes during the installation of the electrodes and thermowells on top of the treatment zone and treat them with the undisturbed soil. Alternatively, the cuttings can be drummed and treated or disposed of as was done during the SITE demonstration.

Depending on its design, the vapor treatment and collection systems may generate residuals. The materials handling requirements for these residuals will vary depending on the design of the vapor treatment system and the contaminants present in the soil. During the SITE demonstration, uncondensed vapors were channeled directly to a propane-fueled flare. Vapors that condensed in the vapor collection system were collected in a 50-gallon (0.19-cubic-meter) drum. The drum contents were pumped as required to the 20,000-gallon (76-cubic-meter) tank used to store water from dewatering activities. The contents of the 20,000-gallon (76-cubic-meter) tank were periodically transferred to a Kelly APB industrial wastewater treatment facility for treatment. The residuals generated by the vapor treatment system of a commercial-scale RFH system will depend on the vapor treatment system used and the nature of the site being remediated.

Other aqueous residuals generated during the RFH SITE demonstration included groundwater from the dewatering wells and washwater from PPE and equipment decontamination. During the demonstration, 325,920 gallons (1,234 cubic meters) of groundwater were removed from the soil, stored in the same 20,000-gallon (76-cubic-meter) tank, and then periodically transferred to the Kelly AFB wastewater treatment facility for treatment.

2.7 SITE SUPPORT REQUIREMENTS

The site must be prepared for the mobilization, operation, maintenance, and demobilization of the equipment. Access roads are needed for equipment transport. Approximately 4600 square feet (427 square meters) of a relatively flat surface are needed to accommodate the trailer-mounted RF generators, controllers, and other support equipment for the full-scale system. Therefore, a portion of the site may require grading

Remediation using a full-scale RFH process will require that certain utilities be available at the site. Water must be available for steam-cleaning the drill rig and other equipment and personnel decontamination activities. Electrical power must also be available. It is projected that 480-volt, 3-phase power will be provided at an onsite distribution point, and that a 3-phase delta-wye 480- to 240-volt transformer will be provided to establish the required single-phase service. The primary component connected to the 480-volt, 3-phase power will be the RF generator; the majority of the other system components will use 240-volt, single-phase power. The average hourly electrical usage rates during heating and cooldown are estimated to be 439.5 kW and 53.25 kW, respectively.

Monitoring should be conducted to ensure that the RF field outside of the treatment zone does not exceed National Institute for Occupational Safety and Health (NIOSH) or FCC requirements. During the SITE demonstration, these measurements were reportedly performed by IITRI.

A mobile drill rig and drill crew will be required onsite for the collection of soil samples and for the installation and removal of all subsurface components. The drill rig will also be used to install dewatering wells if dewatering is necessary. A bermed area will be required for the decontamination of the drill rig. A forklift and operator will be required during assembly and disassembly.

Residuals collected from the vapor treatment system, groundwater collected during dewatering (if dewatering is required), and water used in decontamination activities may be hazardous and the handling of these materials requires that a site plan be developed to provide for personnel protection and special handling measures. Storage should be provided to hold these wastes until they have been tested to determine their acceptability for disposal or release to a treatment facility.

2.8 LIMITATIONS OF THE TECHNOLOGY

The performance of the RF technology is very dependent on the classification of the soil present at the site. Therefore, it is highly recommended that site-specific treatability and soil air permeability tests be performed prior to implementing the technology.

Soils containing large amounts of silt, clay, and humic substances tend to adsorb organic contaminants more tightly, making it more difficult for contaminant removal to occur. Soils containing a large fraction of clay may also have insufficient air permeability and thus impede the ability of the SVE system to remove the volatilized contaminants. The soils treated during the SITE demonstration were

very heterogeneous. Some zones within the treatment area were highly permeable (primarily gravel or sandy soil); other zones consisted of a large percentage of silt and clay (up to 78 percent). Extraction of vapors from such soils frequently bypasses lower-permeability zones, leaving contaminants behind.

Wet soils normally have low air permeabilities because void spaces are filled with water. RFH, in conjunction with SVE, will tend to dry soils and increase the air permeability of wet soils. Therefore, RFH is likely applicable to Wet Soils. However, IITRI's RFH technology is not generally recommended for the remediation of saturated soils. If saturated soil is to be remediated by RFH, the treatment zone should be dewatered prior to treatment. If the water table is close to the contaminated soil and the groundwater is also contaminated, it may be difficult to heat the soil without volatilizing contaminants in the groundwater. Measures may need to be taken to lower the groundwater table in the contaminated area or place a hydraulic barrier (i.e., slurry wall or sheet piling) upstream of the contaminated area to divert aquifer flow around the treatment zone. Based on the results of the SITE demonstration, it is not clear that groundwater levels can be adequately controlled at all sites to permit the proper operation of the RFH system.

IITRI's RFH system can only be used to remove contaminants that can be volatilized at soil temperatures that the system can practically achieve throughout the treatment zone. Inorganics, metals, and other nonvolatile contaminants are normally removed, and higher temperatures may be required for some semivolatile contaminants.

The presence of large inclusions in the area to be heated can limit the use of the RFH process. Inclusions are void volumes, containers, metal scrap, general refuse, demolition debris, rock, or other heterogeneous materials within the treatment volume. Large debris and drums can also interfere with the inhalation of underground system components.

Some soil contaminants may remain after treatment. Although the true effectiveness of the technology during the SITE demonstration cannot be determined due to design and operational problems, it should be noted that quantities of several organics remained in the soil after treatment was completed. (Removal of all contaminants from the revised design treatment zone was not an objective of the demonstration.) Further treatment is required to remediate these soils to the desired cleanup levels. Residuals from vapor treatment, as well as soil Cuttings, groundwater, and decontamination water, may remain after treatment and require further treatment,

IITRI claims its technology is not ready for commercialization. Considerable development and optimization of the process is required before a full-scale system is ready for field use. The IITRI RFH technology cannot be used as a stand-alone technology since it requires the use of a vapor treatment system to treat the volatilized contaminants that are removed from the soil.

2.9 REFERENCES

1. Dev, H., J. Enk, G. Sresty, J. Bridges, and D. Downey. In Situ Soil Decontamination by Radio-Frequency Heating-Field Test. Prepared by IIT Research Institute for Air Force Engineering & Services Center. September 1989.
2. Roy F. Weston, Inc. Rocky Mountain Arsenal In Situ Radio Frequency Heating/Vapor Extraction Concept Engineering Report. November 1992.
3. Engineering Bulletin: In Situ Soil Vapor Extraction Treatment. EPA/540/2-91/006, May 1991.
4. Engineering Bulletin: In Situ Steam Extraction Treatment. EPA/540/2-91/005, May 1991.

SECTION 3

ECONOMIC ANALYSIS

3.1 INTRODUCTION

The primary purpose of this economic analysis was to estimate the costs (not including profit) for using IITRI's in situ RFH technology on a commercial-scale level to remediate soil contaminated with TRPH, VOCs, and SVOCs. The primary cost analysis is based on the results of the SITE demonstration that utilized IITRI's 40-kW pilot-scale RFH system, information from previous tests conducted by IITRI, and information obtained from engineering textbooks. The second analysis is based on a theoretical RF design and treatment zone, information provided by IITRI, bench-scale tests, and information obtained from engineering textbooks. The results of the second analysis are not discussed in detail in this section; they are only summarized in Subsection 3.4.

Demonstration results were adversely affected by several problems associated with the design and operation of the RFH system, as discussed in Subsection 2.2. The developer has stated that a full-scale system would be designed differently than the system used during the demonstration, and that the technology is far from commercialization. These factors made it difficult to prepare the cost estimate, which is typically based on the design and operation of the system during the demonstration. When the technology is ready for commercialization, further economic analyses should be performed. Costs obtained from those analyses would likely be more indicative of costs of the technology at a commercial-scale level.

3.2 BASIS OF ECONOMIC ANALYSIS

This cost analysis was performed in accordance with standard procedures utilized for all SITE Program demonstrations. The cost analysis was prepared by breaking down the overall cost into 12 categories. The cost categories and the areas that each of them generally comprise are listed in Table 3. Because some of the cost categories are very site-specific, no economic analysis of these categories was performed.

Table 3. Twelve Cost Categories for the IITRI SITE Demonstration Economic Analysis

<ul style="list-style-type: none">• Site preparation<ul style="list-style-type: none">– site design and layout– surveys and site logistics– legal searches– access rights and roads– land clearing– preparations for support and decontamination facilities– utility connections– auxiliary buildings• Permitting and regulatory<ul style="list-style-type: none">– actual permit costs– system monitoring requirements• Equipment<ul style="list-style-type: none">– equipment used during treatment– freight– sales tax• Startup and fixed<ul style="list-style-type: none">– transportation of personnel to the site– wages and living expenses– assembly of the unit– shakedown, testing, and training– working capital– insurance– contingencies– property taxes– process monitoring equipment– engineering and supervision	<ul style="list-style-type: none">• Operating Costs for Treatment<ul style="list-style-type: none">– labor– fabrication– drilling• Supplies<ul style="list-style-type: none">– spare part(s)– bentonite• Consumables<ul style="list-style-type: none">– electricity– water– diesel fuel• Effluent treatment and disposal<ul style="list-style-type: none">– further treatment/disposal of effluent(s)– onsite storage of effluent(s)• Residuals and waste shipping, handling, and transport<ul style="list-style-type: none">– storage of residuals/wastes– transportation of residuals/wastes– treatment/disposal of residuals/wastes• Analytical services<ul style="list-style-type: none">– sampling and analytical program• Facility modification, repair, and replacement<ul style="list-style-type: none">– maintenance material costs– design adjustments– equipment replacements• Site demobilization<ul style="list-style-type: none">– disassembly costs– site cleanup and restoration– wages and living expenses
--	--

3.3 ISSUES AND ASSUMPTIONS

This subsection summarizes the issues and assumptions of the economic analyses for this study. The original objective of this SITE demonstration was to treat a single cell having dimensions of 17.5 feet (5.33 meters) by 10.0 feet (3.05 meters) by 29.0 feet (8.84 meters); the total volume was 188 cubic yards (144 cubic meters) or approximately 254 tons (230 metric tons). However, due to the presence of a shallow groundwater table prior to installation, the lengths of the exciter electrodes were decreased to 20.0 feet (6.10 meters). This design change and operational problems during the demonstration resulted in an effective heating length of 14.1 feet (4.30 meters), and an effective heating depth of 24.0 feet (7.32 meters). The width remained at 10 feet (3.0 meters). This zone is referred to as the "revised design treatment zone." The primary economic analysis is based on the revised design treatment zone. Contaminant removals calculated for the revised design treatment zone and for the heated zone, which is defined in Subsection 2.2, are presented in Subsection 4.3.1. An economic analysis of the heated zone was not performed.

For the primary analysis, the goal was to estimate remediation costs of a full-scale system based upon a site of approximately 10,000 tons (9,072 metric tons) at a depth of 24 feet (7.3 meters). The size of the full-scale system was estimated to be 300 kW based on input from the developer. Since a 40-kW unit was used during the SITE demonstration, a factor of 7.5 (300 kW divided by 40 kW) was used to scale-up the RF system and treatment volume used in the SITE demonstration to the full-scale level. The volume of each cell at the full-scale level was determined to be 25,380 cubic feet (940 cubic yards or 719 cubic meters). However, since much of the revised design treatment zone did not achieve the desired temperatures, a decision was made that the width and depth of the scaled-up cells would remain equal to the width (10 feet or 3.0 meters) and depth (24 feet or 7.3 meters) of the cells in the SITE demonstration. Knowing the volume, width, and depth of the full-scale cells, the length of each cell was determined to be 105.75 feet (32.23 meters). Based upon these dimensions and a soil density of 1.35 tons per cubic yard (0.936 metric tons per cubic meter), it was determined that the mass of eight cells (10,152 tons or 9,210 metric tons) would be the mass used for this analysis since it most nearly meets the 10,000-ton (9,072-metric-ton) goal.

Several assumptions about the technology were made and are discussed in the following subsections. Even though the RFH system did not achieve the objective of maintaining a temperature of 150°C (302°F) throughout the revised design treatment zone and showed a lack of contaminant removal during the SITE demonstration, this economic evaluation assumes the technology will achieve an average treatment temperature of 150°C (302°F) and remove contaminants to necessary cleanup levels. The actual treatment temperature, duration the temperature is maintained, and cleanup levels are site-specific.

It is assumed that the RFH system will operate 24 hours per day, 7 days per week, with a 95 percent online time. The online factor is used to adjust the unit treatment cost to compensate for the fact that the system is not online constantly because of maintenance requirements, breakdowns, and unforeseeable delays, and considers fixed costs incurred while the system is not operating. The total estimated time the equipment will be onsite is approximately 104 weeks. This is based on the following time estimates:

<u>Activity</u>	<u>Weeks</u>
Set up equipment, etc.	1
Assemble and install electrodes	6.4
Connect aboveground and subsurface components	1
Shakedown and testing	2
Heating at 9 weeks each for 8 cells	72
Total time to mobilize from cell to cell	7
Cooldown	8
Remove subsurface components	6.4
TOTAL	103.8

The following subsections (Subsections 3.3.1 through 3.3.12) describe assumptions that were made in determining project costs for 7 of the 12 cost categories. This analysis does not include cost values for: site preparation; permitting and regulatory; effluent treatment and disposal; residuals and waste shipping, handling, and transport; and analytical services. Costs for these categories are highly dependent upon site-specific factors, and therefore, no estimates are presented in this economic analysis. Consequently, the actual cleanup costs incurred by the site owner or responsible party can be significantly higher than the costs shown in this analysis. According to the American Association of Cost Engineers, the actual cost is expected to fall between 70 percent and 150 percent of this estimate. Since this cost estimate is based on a preliminary design, the range may actually be wider.

Insurance, property taxes, spare parts, contingency costs, and maintenance materials can be estimated as a percentage of the fixed capital investment required for a project [1]. To determine the fixed capital investment, an algebraic equation was devised using the cost items below:

- Total equipment cost applied to the project (including freight and sales tax)
- 1 year supply of operating supplies (1 percent of fixed capital investment)
- Transportation (other than freight)
- Assembly labor
- Shakedown, testing, and training labor
- Contingencies (10 percent of fixed capital investment)
- Engineering and supervision labor for system installation

Since some of these components are estimated independently of the fixed capital investment (e.g., assembly), and others are percentages of the fixed capital investment applied to the project (e.g., contingencies), a formula for calculating the fixed capital investment was developed.

3.3.1 Site Preparation Costs

The amount of preliminary site preparation required is highly dependent on the site. Consequently, site preparation costs are not included in this cost estimate and are assumed to be the responsibility of the site owner or responsible party. It is essential to consider that site preparation measures may significantly increase the costs associated with the use of this technology.

3.3.2 Permitting and Regulatory Costs

Permitting and regulatory costs can vary greatly because they are site- and waste-specific. Consequently, no permitting or regulatory costs are included in this analysis. This category may be a significant factor in determining project costs since permitting activities can be both expensive and time consuming for any technology. Regulatory approval for the vapor and condensate treatment systems may be required. Regulatory requirements that must be considered when remediation Superfund site are discussed in Subsection 2.1.

3.3.3 Equipment Costs

The primary pieces of equipment of the IITRI RFH system include:

- RF generator
- Control system
- Matching network
- Dummy load
- Ground and exciter electrodes
- Thermocouples and thermowells
- Vapor barrier
- Vapor collection system
- Instrumentation
- Electrical components/wiring

Equipment cost estimates are based on vendor quotes, estimates by B&REyan d IITRI, or information provided by Plant Design and Economics for Chemical Engineer [1]. When necessary, the Chemical Engineering Cost Index [2] is used to estimate current costs from earlier cost data. The annualized cost (rather than depreciation) is used to calculate the annual equipment costs incurred by a site. The annualized cost is calculated using the following formula:

$$A = P \frac{i (1 + i)^n}{(1 + i)^n - 1}$$

where:

- A = annualized cost (\$)
- P = present value principal sum (\$)
- i = interest rate (%)
- n = years

The value "n" is the useful life of the equipment and varies according to the equipment under consideration. The annualized equipment cost, prorated to the actual time the unit is at the remedial site (including assembly, shakedown and testing, treatment, and disassembly), is \$463,097 over a period of 103.8 weeks (1.99 years). The unit is assumed to have no salvage value.

The average price of one 100-kW unit is estimated to be approximately \$175,000 [3]; since the commercial-scale unit will require three 100-kW units, the total cost to the project will be \$525,000. The prices of the control system and 6 X 50 matching networks are estimated to be \$200,000 and \$240,000, respectively [4]. The estimated price for one 100-kW dummy load is estimated to be \$37,000 [4].

The total price for electrodes, thermocouples, and thermowells is estimated to be \$333,925 [5] [6]. It is assumed that enough components for two cells will be purchased. This will enable work to progress to the second cell while the first is in its cooldown period. The ground electrodes are anticipated to run along the length of the cell to be heated on the borderline separating one cell from the next. Therefore, savings will occur since one of the ground electrode rows in the first cell can be used in the heating of the second cell while the first cell is in its cooldown period. One row of the ground electrodes in the second cell can be used in the heating of the third cell and so on.

The RF shield cost is estimated to be \$4,996. The vendor claims that the RF shield is a site-specific item that may not be needed when the IITRI system is operated at a frequency of 6.78 MHz or lower. However, since the RF shield was used during the SITE demonstration, it is included in this cost estimate. The vapor collection system cost is estimated to be \$12,348, based upon prices obtained from a parts catalog [7]. The vapor treatment system is site-specific and is not included in this economic analysis.

Instrumentation cost for the system is assumed to be 6 percent of the total purchased equipment cost and estimated to be \$102,948 for the project. Electrical installation costs are assumed to be 10 percent of the total purchased equipment cost and estimated to be \$171,580 for the project. Freight costs are assumed to be 7 percent of the total equipment purchase cost and estimated to be \$120,106 for the project. The percentages used to estimate costs for instrumentation, electrical installation, and freight are based on information provided by Plant Design and Economics for Chemical Engineer [1]. Sales taxes are assumed to be 5.5 percent of the total equipment purchase cost and their costs are estimated to be \$94,369 for the project. When these costs are added to the total equipment purchase cost, the overall equipment cost is estimated to be \$1,930,272. Table 4 summarizes all IITRI RFH equipment costs.

Table 4. Summary of IITRI RFH Equipment Costs

Component	Cost
RF Power Sources	\$525,000
Control System	\$200,000
Matching Networks	\$240,000
Dummy Load	\$37,000
Trailers	\$88,000
Electrodes	\$171,204
Thermocouples and Thermowells	\$162,721
RF Shield	\$4,996
Vapor Collection System	\$12,348
Instrumentation	\$102,948
Electrical	\$171,580
Freight	\$120,106
Sales Tax	\$94,369
TOTAL	\$1,930,272

3.3.4 Startup and Fixed Costs

Transportation activities include moving the IITRI system to the site. Transportation costs for equipment are covered under the freight charge applied to the total equipment purchase cost discussed in Subsection 3.2.3.

Assembly consists of unloading the system from the trailer and assembling it at the site. It is assumed that one forklift at \$325 per hour and one operator at \$25 per hour will be required. The cost to transport the forklift to and from the site is \$55 per hour, and it is assumed that it will take 4 hours to drop off and pick up the forklift. The total cost is estimated to be \$1,545.

It is estimated that 10.4 weeks will be required to set up equipment onsite, fabricate and install electrodes and thermowells, assemble the above-ground system components, and shakedown and test the unit. Assembly and shakedown and testing are assumed to require five people (four technicians and one project manager). The assembly will consist of two 2-person crews for 8 hours per day, 5 days per week each. Each shift will consist of two technicians. It is estimated the project manager will spend 20 hours on the project during assembly. It is assumed that the technicians will be temporarily relocated by IITRI to the general area in which the site is located. However, it is assumed that the technicians will not be paid for travel or living expenses. Therefore, to compensate for the lack of living and travel expenses, it is assumed that IITRI will increase the hourly salaries the technicians would be paid if the site were local by a factor of 1.33. A multiplier of 1.8 was then applied to each of the worker's salaries to cover benefits and other overhead costs. The estimated labor cost for assembly and shakedown and testing is \$70,986. Listed below are the fully-burdened costs (including wages, benefits, and overhead) for all onsite personnel involved with assembly and all other phases of the project.

- Operator/technician – \$35.91/hour
- Project Manager – \$54/hour

Working capital consists of supplies, utilities, spare parts, and labor necessary to keep the RFH system operating without interruption due to financial constraints [1]. The working capital for this system is based on maintaining 2 months of payroll for labor, 2 months of payroll for the drilling subcontractor, and 1 month of inventory of the other items. For the calculation of working capital, 1 month is defined as one-twelfth of 1 year. Working capital for one month is estimated to be \$204,782. The annual cost of borrowing the working capital (at an 8.5 percent interest rate) for the time the equipment is operating is \$116,121. Therefore, the total working capital cost for this project is \$231,161.

Insurance is assumed to be 2 percent of the fixed capital investment and the cost is estimated to be \$45,007 per year and \$89,594 for the project. Property taxes are assumed to be 3 percent of the total fixed capital investment [1] and the costs are estimated to be \$67,510 per year and \$134,392 for the project.

The cost for the initiation of process monitoring programs is not included in this estimate. Depending on the site, local authorities may impose specific guidelines for monitoring programs. The stringency and frequency of monitoring requirements may have a significant impact on the project costs. Air monitoring will likely be required due to the potential release of air emissions during treatment.

A contingency cost is included to cover additional costs caused by unforeseen or unpredictable events, such as strikes, storms, floods, and price variations [1]. The total contingency cost during the life of the system is estimated to be 10 percent of the fixed capital investment. The annual contingency cost is \$29,865 to the project.

3.3.5 Operating Costs for Treatment

Treatment operations (soil heating) for the RFH system will be conducted 24 hours per day, 7 days per week, for 79 weeks. It is assumed that energy will be applied to each cell for a total of 9 weeks (same duration that energy was applied during the SITE demonstration). It is also assumed that it will take 1 week to move from one cell to another; therefore, this will add 7 weeks to the total treatment time. Labor costs consist of fully-burdened personnel costs for five personnel. Fully-burdened personnel costs were provided in Subsection 3.3.4. The treatment labor force will be structured as described in Subsection 3.3.4. The total labor cost for treatment is estimated to be \$1,038,515.

It will be necessary to subcontract a drilling company for the installation and removal of the electrodes and thermowells. A two-person crew will operate the drill rig. Depths of the boreholes are assumed to be:

Ground electrodes	– 24 feet (7.3 meters)
Exciter electrodes	– 20 feet (6.1 meters)
Thermowells	– 24 feet (7.3 meters)

The cost for drilling a 6-inch (0.15 meters) diameter hole with a hollow stem auger is assumed to be \$12.25 per foot (\$40.19 per meter). The estimated costs for installing and removing the subsurface components are \$6.50 and \$2.50 per foot (\$21.33 and \$8.20 per meter) respectively. The total drilling costs for the project are estimated to be \$992,616 and assume that a geologist is not required for drilling oversight and soils characterization.

3.3.6 Cost for Supplies

For this technology, supplies consist of spare parts and bentonite for backfilling the boreholes after the extraction wells and thermowells are installed. Annual operating supply costs are estimated to be 1 percent of the fixed capital investment [1], which is approximately \$22,503 per year and \$44,797 for the entire project.

Bentonite used to backfill the boreholes after the extraction wells and thermowells are installed is assumed to cost \$7 per bag with each bag containing 50 pounds (22.7 kilograms) of bentonite chips. It is estimated that 4,116 bags of bentonite will be required for the project at a total cost of \$28,815.

3.3.7 Cost for Consumables

Electricity is required not only during the heating of the cell but also during its cooldown period (equipment such as the blower, lighting, and instrumentation will continue to operate during cooldown). The average hourly power usage rates during the heating and cooling periods are estimated to be 439.5 and 53.25 kW, respectively. Based upon a 9-week duration for heating and 8-week duration for a cooldown period for each cell, the total electricity cost for the project (eight cells) is approximately \$453,433 (at a rate of \$0.077 per kWh).

In order to implement the IITRI RFH technology, the site must have a supply of uncontaminated water available. Water will be used for decontamination of the drill rig augers and be added to the bentonite used in backfilling the boreholes and is estimated to be 600 gallons (2.3 cubic meters) per day. A sewerage charge is assumed for all water used. Based upon 600 gallons (2.3 cubic meters) per day and rates provided by the Cincinnati Water Works, the total water and sewerage bill for the project is estimated to be \$1,794.

Diesel fuel will be required to heat the four onsite project trailers. Diesel fuel is assumed to cost approximately \$1.25 per gallon (\$0.33 per liter) and \$7,266 for the project.

3.3.8 Cost for Effluent Treatment and Disposal

The design of the vapor treatment system will vary depending on the contaminants present in the soil and may generate residuals. Condensate may form in the vapor collection and treatment systems and require treatment. Washwater from PPE decontamination may require treatment. Therefore, for the

purposes of this report, since these items are site-specific and assumed to be the obligation of the site owner or responsible party, they are not included in this analysis.

3.3.9 Residuals and Waste Shipping, Handling, and Transport Costs

If the treatment area extends below the natural water table, it will be necessary to install dewatering wells to lower the water table. The groundwater pumped out of these dewatering wells is likely to be contaminated. However, because dewatering will only be required at some sites and because the quantity of groundwater removed and the contaminants present in the groundwater will vary from site to site, this site-specific cost is assumed to be the obligation of the site owner or responsible party and thus is not included in this estimate.

Several boreholes will be drilled for installation of the extraction wells and electrodes. The soil cuttings removed from these boreholes will be contaminated and will require treatment. During the demonstration, these cuttings were drummed for subsequent treatment and disposal. IITRI claims that soil cuttings can be placed on top of the soil surface and treated along with the undisturbed soil. It is assumed that the same procedure will be followed during full-scale treatment. If the cuttings are not treated along with the undisturbed soil, they will be a contaminated residual. The residual treatment cost is also assumed to be the obligation of the site owner or responsible party and is not included in this estimate.

3.3.10 Cost for Analytical Services

No analytical costs are included in this cost estimate. The responsible party may elect or may be required by local authorities to initiate a sampling and analytical program at its own expense. If specific sampling and monitoring criteria are imposed by local authorities, these analytical requirements can contribute significantly to the cost of the project.

3.3.11 Facility Modification, Repair, and Replacement Costs

Maintenance costs vary with the nature of the waste and the performance of the equipment and include costs for design adjustments, facility modifications, and equipment replacements. For estimating purposes, annualized maintenance costs (excluding labor) are assumed to be 3 percent of the fixed capital investment [1] and are estimated to be \$67,510 per year and \$134,392 for the project.

3.3.12 Site Demobilization Costs

It is assumed that the transportation costs in the demobilization phase will be equal to the transportation costs of the assembly phase of the project. Therefore, the cost for site demobilization is estimated to be \$1,545. It is assumed that a total of 14.4 weeks will be required for disassembly of the above-ground components and for preparation time needed to remove the equipment from the site. Labor will be structured as described in Subsection 3.3.4 and will cost approximately \$98,289.

It is assumed that much of the demobilization will occur while the cell is in its cooldown period. It is estimated that it will take 8 weeks for each cell to cool down. However, the time required to cool down will only add 8 weeks to the total time onsite for the last cell, since everything except the duplicated components can be removed during cooldown.

3.4 RESULTS OF THE ECONOMIC ANALYSIS

This subsection summarizes the results of the economic analyses of the IITRI RFH system treating 10,152 tons (9,210 metric tons) of soil based upon a scale-up of the SITE demonstration and 8,640 tons (7,838 metric tons) based upon a theoretical RF design and treatment zone. In both cases, the developer claims that the RF system is capable of operating with an online factor of 95 percent on a full-scale level and will heat and maintain the desired treatment temperature throughout the zone under consideration. The treatment temperature and the duration the heat will be applied are determined on a site-specific basis.

Table 5 summarizes the estimated treatment costs per ton using the IITRI RFH system in the treatment of 10,152 tons (9,210 metric tons) of soil with an online percentage of 95 percent. Table 5 also presents the treatment costs of each of the 12 cost categories as a percentage of the total cost. Table 6 summarizes the estimated treatment costs of the theoretical RF design and treatment zone. The actual cost is expected to fall between 70 and 150 percent of the estimated cost.

Table 5 indicates that the RFH system costs approximately \$370 per ton (\$410 per metric ton) to remediate a 10,152-ton (9,210 metric ton) site. Table 6 indicates that the costs of implementing the theoretical RF design and treatment zone at a site containing 8,640 tons (7,838 metric tons) is estimated to be \$195 per ton (\$215 per metric ton). This cost estimate is based on information and assumptions supplied by IITRI that were input into the standard SITE cost estimating procedures. These assumptions and IITRI's theoretical design were not verified during the SITE demonstration.

**Table 5. Treatment Costs for the IITRI RF' System Treating 10,152 Tons of Soil
(Scaled-up from the Results of the SITE Demonstration)**

Item	Unit Cost		
	\$/ton	\$/metric ton	cost (96 of total cost)
Site preparation	NE	NE	NE
Permitting and regulatory	NE	NE	NE
Equipment	45.62	50.29	12.3
Startup and fixed	47.93	52.83	13.0
Operating costs for treatment	200.07	220.54	54.1
Supplies	7.25	7.99	2.0
Consumables	45.56	50.22	12.3
Effluent treatment and disposal	NE	NE	NE
Residuals and waste shipping, handling, and transport	NE	NE	NE
Analytical	NE	NE	NE
Facility modification, repair, and replacement	13.24	14.59	3.6
Site demobilization	9.83	10.84	2.7
Total operating costs	369.50	407.30	100

NE = Not estimated in the analysis. The cost for this item is highly dependent on site-specific factors

**Table 6. Treatment Costs for the IITRI RF System Treating 8,640 Tons of Soil
(Based upon a Theoretical RF Design and Treatment Zone)**

Item	Unit Cost		
	\$/ton	\$/metric ton	cost (% of total cost)
Site preparation	NE	NE	NE
Permitting and regulatory	NE	NE	NE
Equipment	30.76	33.91	15.8
Startup and fixed	36.75	40.51	18.9
Operating costs for treatment	75.7	83.44	38.8
Supplies	3.83	4.22	2.0
Consumables	14.88	16.40	7.6
Effluent treatment and disposal	NE	NE	NE
Residuals and waste shipping, handling, and transport	NE	NE	NE
Analytical	NE	NE	NE
Facility modification, repair, and replacement	8.60	9.48	4.4
Site demobilization	24.37	26.86	12.5
Total operating costs	194.89	214.82	100

NE = Not estimated in the analysis. The cost for this item is highly dependent on Site-specific factors.

3.5 REFERENCES

1. Peters, M.S. and K.D. Timmerhaus. Plant Design and Economics for Chemical Engineers, Third Edition. McGraw-Hill, Inc., New York, 1980.
2. Chemical Engineering. McGraw-Hill, Inc., Volume 102, Number 1, January 1995.
3. Cost determined based upon an average of estimates from vendors,
4. Information provided by IITRI.
5. Cole-Parmer 19951996 Catalog. Niles, Illinois.
6. Consolidated Plastics Catalog. Twinsburg, Ohio, 1994.
7. Grainger Industrial and Commercial Equipment and Supplies 1994 Catalog. Lincolnshire, Illinois, 1994.

SECTION 4

TREATMENT EFFECTIVENESS

4.1 BACKGROUND

The SITE demonstration of IITRI's RFH system took place at spill Site S-1 at Kelly AFB in San Antonio, Texas. From 1960 to 1973, Site S-1 was used as an intermediate storage area for wastes awaiting offsite reclamation. Waste liquids including mixed solvents, carbon cleaning compounds, petroleum oils, and lubricants were temporarily stored in tanks located within this area. Spills during waste transfer operations and flooding of storage tanks are reported to have caused the current soil contamination. After waste transfer operations at the site were halted, the tanks were removed, the sump and depression were backfilled, and the area was graded. Soil contamination persists down to and in the saturation zone, which begins approximately 25 to 30 feet (7.6 to 9.1 meters) below the surface.

The original design treatment zone was 10.0 feet (3.05 meters) wide, 17.5 feet (5.33 meters) long, and 29.0 feet (8.84 meters) deep. However, due to shallow groundwater and operational problems during the demonstration, the original RFH design was modified and the volume of the soil to be heated was decreased. The exciter electrodes were raised to a depth of 19.5 feet (5.94 meters below the surface), resulting in an effective heating length of 14.1 feet (4.30 meters) and an effective heating depth of 23.3 feet (7.10 meters). The width remained at 10.0 feet (3.05 meters). This volume is referred to as the "revised design treatment zone." It was the intention of the developer to heat the soil in the revised design treatment zone to 150°C (302°F) during the demonstration and maintain it at that temperature for 4 days. However, soil temperature results indicated a lack of significant heating in remote areas of the revised design treatment zone. As discussed in Subsection 2.2, the volume of soil in the revised design zone that did achieve 150°C (302°F) and maintain it for 2 weeks is referred to as the "heated zone." The dimensions of the heated zone are 10.8 feet (3.29 meters) long, 5.7 feet (1.7 meters) wide, and 20.0 feet (6.10 meters) deep.

The goal of this demonstration was to evaluate the ability of the IITRI RFH technology to remove TRPH, SVOC, and VOC contaminants from the in situ soil. Determination of whether the technology met the goal was based upon contaminant concentration changes in the pre- and post-treatment matched

boreholes or pairs (i.e., final boreholes were placed as close as possible to the original boreholes and samples were collected from the same depth). The requirement for pre- and post-treatment data matched pairs is summarized in Appendix A.

Population distributions for most contaminants were log-normal, and as a result, concentration data were log-transformed. The log-transformed ratio of the post-treatment concentration to the pretreatment concentration was calculated for each sample of each contaminant. The ratios were evaluated statistically using a 2-sided *t* test to determine whether the contaminant concentration had exhibited a statistically significant change between the pre- and post-treatment sampling events. A detailed description and application of the paired *t* test are presented in Appendix A. A preliminary statistical evaluation was performed for the original design treatment zone before IITRI requested that the size of this zone be modified. This evaluation was based on an 80 percent confidence level. The eight contaminants that were found to have statistically significant concentration changes in the preliminary evaluation were evaluated under a final statistical evaluation which was based on a 90 percent confidence level. The geometric mean ratio of post-treatment concentrations to pretreatment concentrations was also calculated. This geometric mean ratio was converted to a geometric mean percent decrease or a geometric mean percent increase, as appropriate. Upper and lower 90 percent confidence intervals were also determined for the revised design treatment and heated zones and are presented in Appendix A.

Because the final statistical evaluation included only those contaminants that exhibited statistically significant changes in the preliminary evaluation, this evaluation focuses on those compounds whose concentrations changed between pre- and post-treatment sampling. Numerous other compounds did not exhibit statistically significant changes in concentration. These compounds are not discussed in detail because it was often difficult to determine why the concentration of a given compound did not exhibit a statistically significant change. Some contaminants may have been unaffected by the RFH technology. Other contaminants, however, may have had initial concentrations so low that a statistically significant change would have been difficult to demonstrate. As a result, the contaminants that did not exhibit statistically significant changes are not discussed to avoid potential misinterpretation. The procedure for determining which contaminants would be evaluated is described in greater detail in Appendix A.

Prior to the demonstration, concentrations of TRPH and certain individual SVOCs and VOCs were designated as “critical” measurements because they were expected to be present in the highest concentrations. Concentrations of all other SVOCs and VOCs were considered “noncritical”

measurements. The critical SVOCs and VOCs were selected based on preliminary data and pretreatment sampling results from Site S-1. The critical SVOCs were 1,2-dichlorobenzene; 1,3-dichlorobenzene; 1,4-dichlorobenzene; 2-methylnaphthalene; and naphthalene. None of the critical SVOCs met the criteria for inclusion in the final statistical evaluation. The critical VOCs were benzene, toluene, ethylbenzene, chlorobenzene, and total xylenes. Only one of the critical VOCs, chlorobenzene, met the criteria for inclusion in the final statistical evaluation.

The noncritical SVOCs selected for the final statistical evaluation were pyrene and bis(2-ethylhexyl)phthalate. Although bis(2-ethylhexyl)phthalate is a common laboratory contaminant, the evidence strongly supports the concentrations measured during this demonstration. The bis(2ethylhexyl)-phthalate concentrations measured in the samples were significantly higher than those measured in the blanks. In addition, the USAF contractor has indicated that bis(2-ethylhexyl)phthalate was used at Kelly AFB as a plasticizer.

The noncritical VOCs selected for the final statistical evaluation were 2-hexanone, 4-methyl-2-pentanone, acetone, and methyl ethyl ketone. All critical and noncritical SVOCs and VOCs are listed in Appendix A. The contaminant removal results are summarized in Subsection 4.3. SITE personnel also performed particle size distribution analyses on the soil to characterize the size and to determine if the technology altered the distribution from pre- to post-treatment soil sampling. Moisture analyses were also performed to convert soil sample concentration results to dry weights.

B&RE also evaluated IITRI's RFH system in terms of operational features by performing (or subcontracting to IITRI) the following tasks (see Appendix A for details):

- Measuring soil temperature in the revised design treatment zone (IITRI)
- Analyzing the SVE vapor stream to determine contaminant removal (B&RE)
- Analyzing the groundwater collected from the dewatering wells and condensate collected in the vapor collection system (B&RE)
- Measuring RF fields radiating from the test array (IITRI)
- Electrical usage (B&RE)

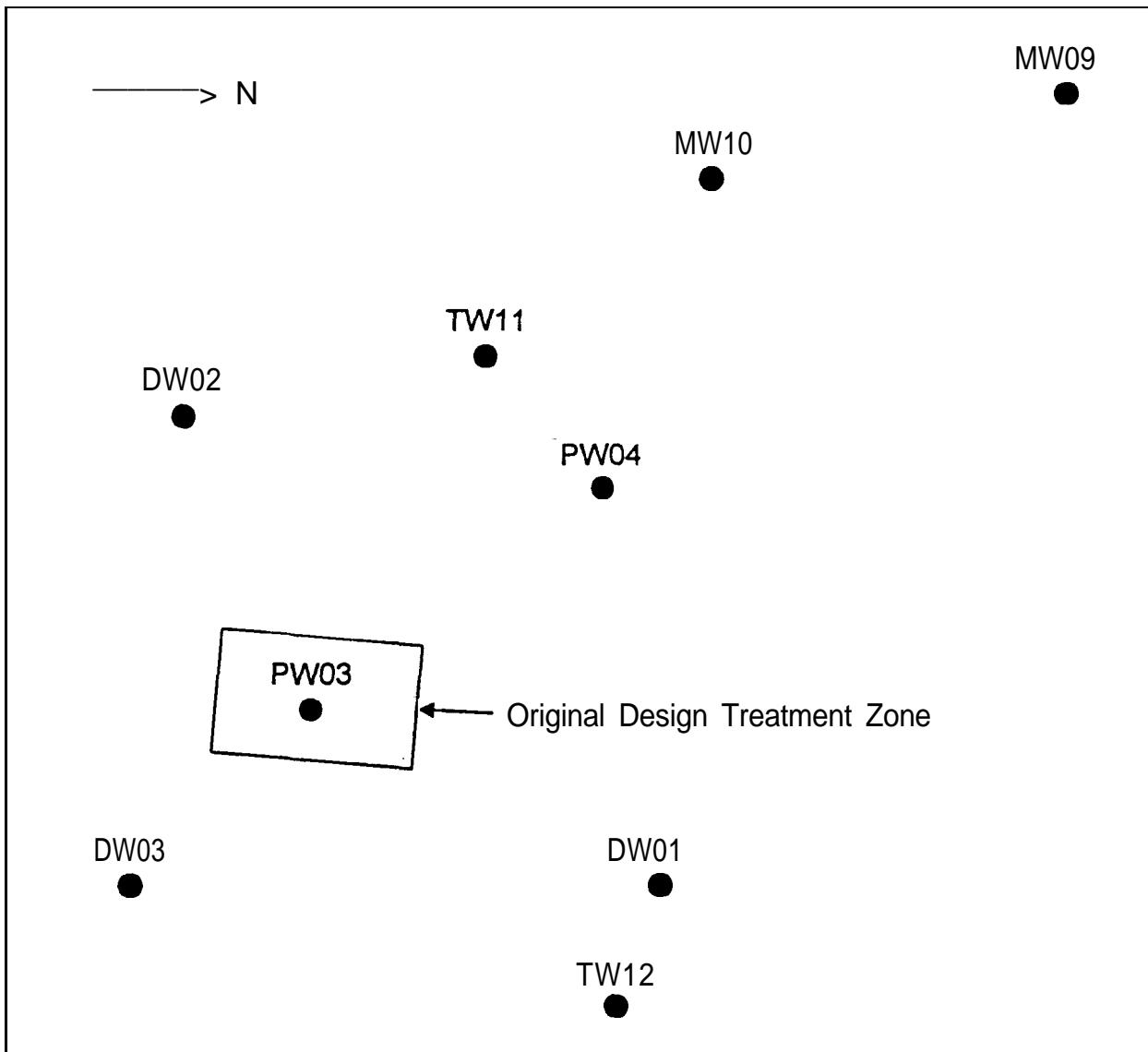
4.2 METHODOLOGY

4.2.1 Soil Sampling

Pretreatment sampling was conducted from January 25, 1993 - February 6, 1993. B&RE used a mobile, hollow-stem auger drill rig to drill 10-inch (0.25meter) diameter boreholes for the installation of the thermowells and electrodes. Figure 4 shows the locations of all electrodes and thermowells used in the SITE demonstration.

During installation of the electrodes, B&RE informed Science Applications International Corporation (SAIC), the SITE Program contractor, that the water table was higher than previous studies had indicated and the installation of dewatering web was necessary. The dewatering wells were designed to minimize groundwater interference with the test, since IITRI's RFH technology is designed for the remediation of soils in the vadose zone. B&RE designed, installed, and operated the dewatering system. Due to the shallow groundwater, IITRI and B&RE subsequently decided to raise the exciter electrodes to 19.5 feet (5.94 meters) and evaluate the RFH technology based on the revised design treatment zone. The ground electrodes would have also been shortened from 29 feet (8.8 meters) long to 24 feet (7.3 meters) long, but time and cost limitations associated with USAF funding made this change impractical.

Several problems were encountered during soil sampling. First, pretreatment soil samples were collected down to 30.0 feet (9.14 meters) even though the treatment zone depth had been revised. Then, since the revised design treatment zone was altered to a depth of 23.3 feet (7.10 meters), B&RE decided that no post-treatment samples below 24.0 feet (7.32 meters) would be taken. Consequently, pretreatment samples between 24.0 and 30.0 feet (7.32 and 9.14 meters) were not a part of the evaluation. Second, a portion of the pretreatment samples were taken during the installation of the dewatering wells, before the water table was lowered. According to information provided after the demonstration by B&RE, piezometer PW03 (located in the revised design treatment zone, see Figure 6) indicated that the water table rose to approximately 22.47 feet (6.849 meters) below ground surface during the pretreatment sampling. Therefore, it is estimated that the pretreatment soil samples ranging from approximately 20 to 24 feet (6.1 to 7.3 meters) below ground surface may have been affected by the groundwater table. The groundwater certainly increased the moisture content and may have increased the contaminant concentrations of some pretreatment soil samples; however, there is not enough information to prove or disprove this possibility. Based upon information provided by B&RE after the demonstration, the water table rose to approximately 24.4 feet (7.44 meters) during RFH application. Therefore, it is possible that



● Well for collecting groundwater samples or monitoring groundwater level

← → Scale: 1 inch = 15 feet

Remote wells:

TWO1 was approximately 110 feet south of MW10.

MWRR was approximately 40 feet west of MW09.

MWQQ was approximately 110 feet north of MW09.

MWW was approximately 190 feet north and 330 feet west of MW09.

Figure 6. SITE demonstration monitoring and dewatering wells.

pretreatment soil samples were collected within the zone of saturation even when the dewatering system was operational. The groundwater levels after dewatering was initiated are summarized in Appendix A.

Soil samples were typically collected using 3-inch (0.08-meter) diameter split spoons. The split spoons were pushed or hammered into the soil (at the appropriate location and depth) using the drill rig. The main portion of each split spoon was 2 feet (0.61 meters) long and contained four 6-inch (0.15 meter) long stainless steel liners, which were numbered from bottom to top. The bottom portion of the split spoon, which was approximately 3 inches (0.08 meters) long and called the “shoe,” did not contain any liners.

The soil characteristics at each sampling point affected the number of liners that were filled with soil. The split spoon filled from the bottom: first the shoe filled, then the first liner, then the second liner, and so on. For example, if the split spoon was pushed into the soil 12 inches (0.30 meters) and then hit a large rock that stopped its progress, only the shoe and the first liner would be filled with soil. The second liner would be partially filled with soil. For each given sampling point, one to four liners were filled with soil.

The split spoon was then removed from the borehole and placed on a flat surface covered with clean aluminum foil. The headspace in the liners was monitored using a flame ionization detector (FID). Soil samples were collected for both chemical and particle size distribution analyses. When a soil sample was selected for chemical analysis, the field sampling crew did not remove it from the stainless steel liner in which it was collected; any void spaces were filled with soil from the shoe to minimize contaminant volatilization. The ends of the liners were covered with pre-cut, 4-inch x 4-inch (0. 1-meter x 0. 1-meter) pieces of **Teflon®** that were secured with polyethylene caps. The liners were labeled, sealed in a plastic bag, and placed in a cooler with ice for preservation. When a soil sample was selected for particle size distribution analysis, the field sampling crew removed the sample from its liner and placed it in a plastic bag. When the split-spoon was filled or nearly filled (i.e., three or four liners were full of soil), the second liner was selected for chemical analysis. When only two liners were full of soil, the second liner was selected for chemical analysis. When a chemical analysis field duplicate was collected, the first liner was selected as the chemical analysis field duplicate. When only the first liner was full of soil, it was selected for chemical analysis. No field duplicates were collected if only the first liner was full. After the soil was selected for the chemical analysis, and when appropriate field duplicates had been collected,

a portion of or all of the remaining soil was designated as the particle size sample.

Soil samples were collected at the appropriate locations shown in Figure 7. The sampling depths for each borehole are shown in Figure 8. In Figure 8, shading indicates sampling intervals designated by the sampling plan (an “X” indicates intervals sampled during pretreatment sampling). Two of the pretreatment soil samples were not collected at the depths designated by the sampling plan due to insufficient soil recovery. When insufficient recovery occurred, the next deeper interval was sampled instead. Samples were labeled with identification numbers that identified the borehole and 2-foot (0.61-meter) sampling interval.

Samples, blanks, and quality assurance/quality control (QA/QC) samples were collected and prepared for chemical analysis. For pretreatment sampling, 48 samples were analyzed for TRPH, SVOCs, VOCs, and moisture. The methods used for these analyses and lists of target VOCs and SVOCs are included in Appendix A. Five field duplicates were submitted to be analyzed for SVOCs, VOCs, TRPH, and moisture. Three samples submitted were designated as matrix spike/matrix spike duplicate (MS/MSD) samples for SVOC, VOC, and TRPH analyses. Three field blanks were submitted for TRPH, SVOC, and VOC analyses. Ten trip blanks were submitted to be analyzed for VOCs.

In general, post-treatment samples were collected from boreholes generally placed within 2 feet (0.61 meters) of the corresponding pretreatment boreholes at the previously sampled depths. Figure 8 shows the locations of pre- and post-treatment soil sampling boreholes. Soil samples were typically collected using a 3-inch (0.08-meter) diameter split spoon, although 2-inch (0.05 meter) diameter split spoons were occasionally used during post-treatment sampling in the dry soil to improve soil recovery. However, due to presence of the shallow groundwater, B&RE decided to not take post-treatment samples any deeper than 24 feet (7.3 meters) below ground surface (bgs). Eight pretreatment samples were collected below 24 feet (7.3 meters) bgs. As a result, no analytical results are available to evaluate contaminant concentration changes below the revised design treatment zone. In addition, some difficulty was experienced in the collection of samples above 24 feet (7.3 meters). In particular, five samples were lost due to insufficient recovery in the split spoon, because the soil in certain areas of the treatment zone was extremely dry and would not remain in the split spoon unless a sandcatcher was used. These five samples were collected again at deeper intervals. Three other samples were not collected as a result of problems encountered during drilling. As a result, post-treatment samples taken for chemical analysis

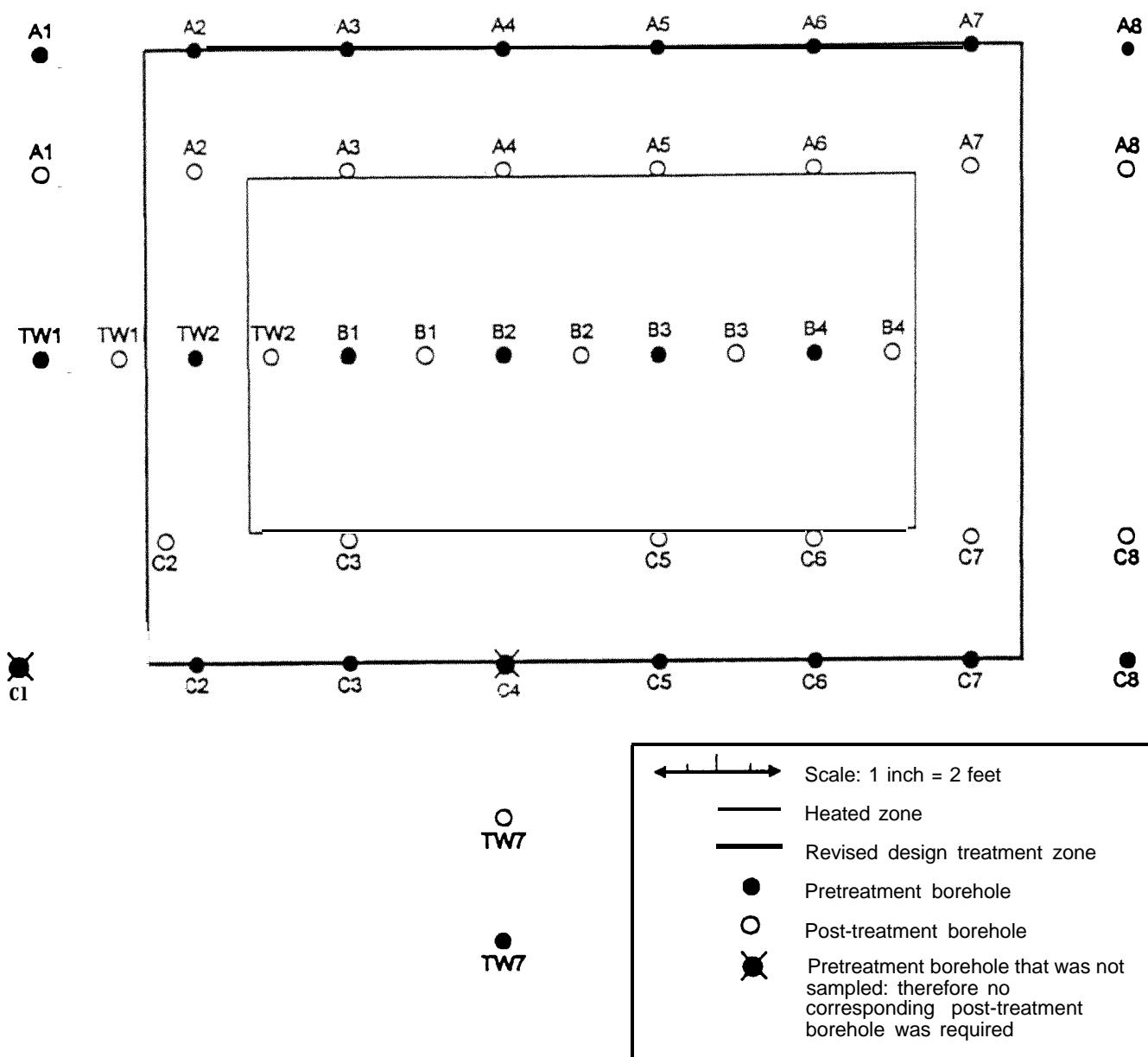
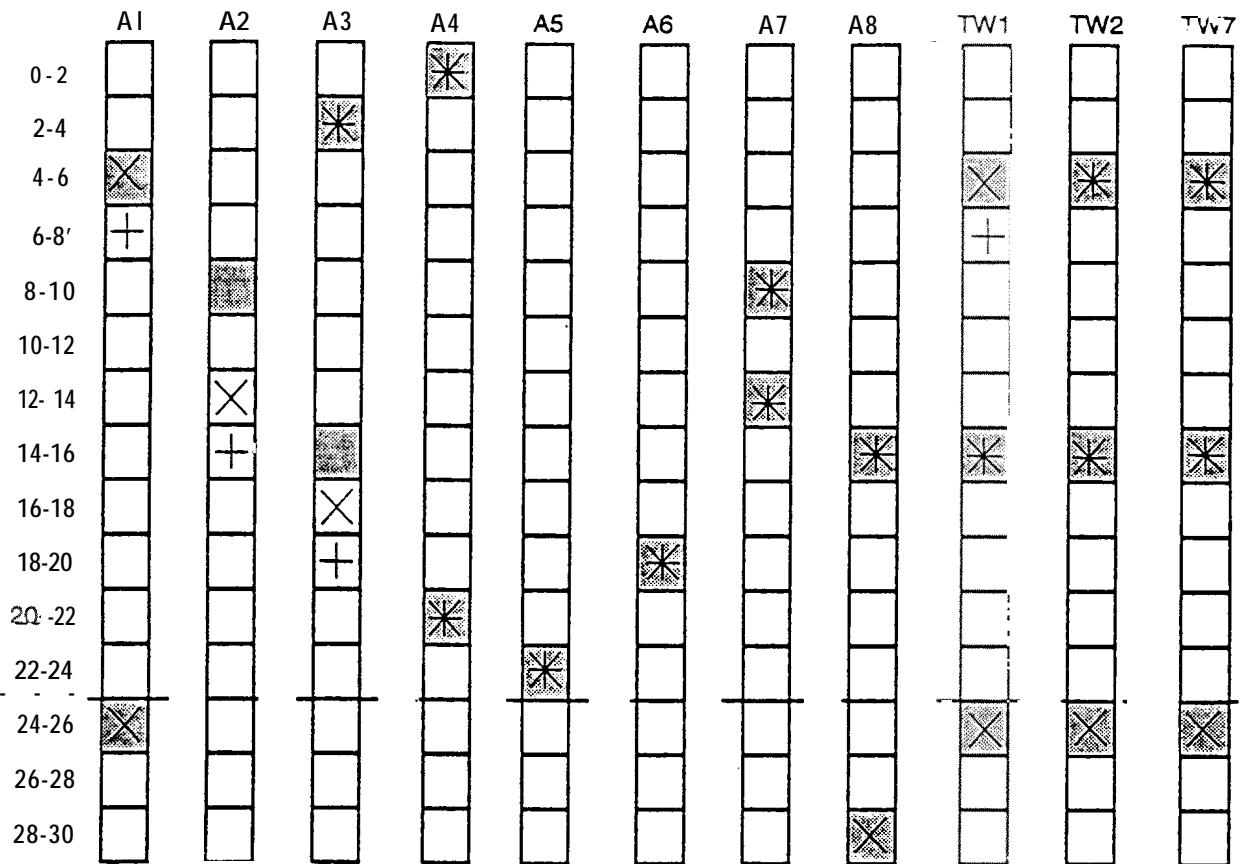


Figure 7. SITE demonstration boreholes.



= designated in sampling plan
 = during pretreatment sampling
 = sampled during post-treatment sampling

Figure 8. Borehole sampling depths

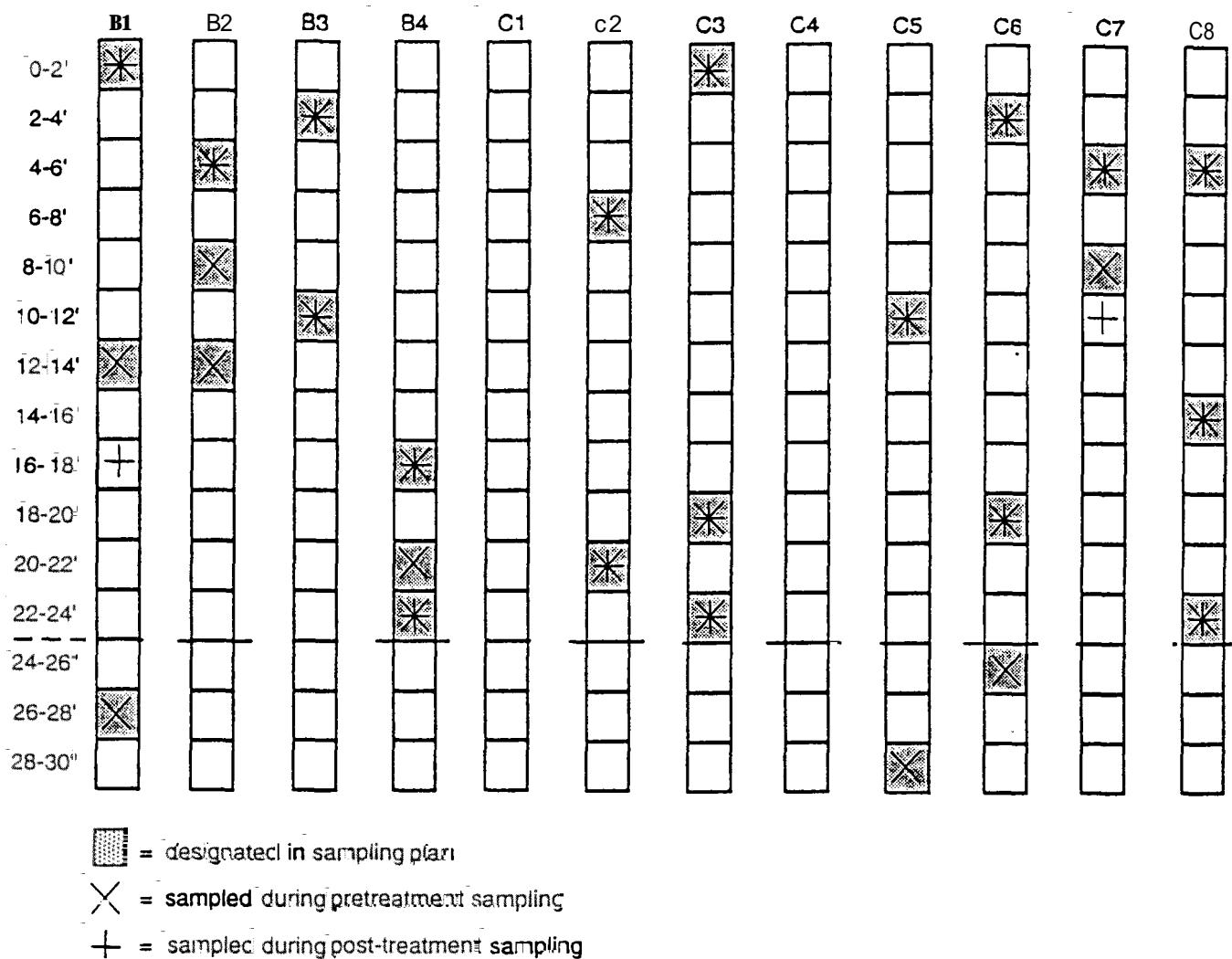


Figure 8. Borehole sampling depths (continued).

were only collected for 37 of the 48 pretreatment samples. Figure 8 shows the actual pre- and post-treatment sampling depths relative to the depths designated in the sampling plan. Pre- and post-treatment samples that were intended to be matched pairs but were not collected from the same depth intervals were still considered matched pairs.

For post-treatment sampling, 37 samples were analyzed for TRPH, SVOCs, VOCs, and moisture. Four field duplicates were submitted to be analyzed for SVOCs, VOCs, TRPH, and moisture. Three samples submitted were designated as MS/MSD samples for SVOC, VOC, and TRPH analyses. Three field blanks were submitted for TRPH, SVOC, and VOC analyses. Five trip blanks were submitted to be analyzed for VOCs.

Forty-four pretreatment samples (plus one laboratory duplicate) and 11 post-treatment samples were submitted for particle size distribution analyses. Field duplicates could not be collected as planned for particle size distribution analysis due to insufficient sample quantities.

The numbers and types of QA samples analyzed for the SITE demonstration are summarized in Table 7. Table 8 summarizes the total number of pre- and post-treatment analyses for samples inside and outside of each treatment zone. As was previously discussed, 11 post-treatment samples were not collected. Poor sample recoveries also altered some pre- and post-treatment sample locations. When sample recovery in a designated interval was inadequate, an attempt was made to collect the sample from the next interval below the designated interval. Such field adjustments to sampling plans are common at sites of this complexity, and resulted in no identifiable impact on the overall soil sampling design. The sampling design was still random in nature since there was no intentional bias associated with changes in locations. Pre- and post-treatment samples that were intended to be matched pairs but were not collected from the same intervals were still considered matched pairs. The criteria for determining 'which matched pairs were to be included in the statistical analysis (complete matched pairs) are described in Appendix A. Table 9 summarizes the number of complete matched pairs for each of the zones under consideration.

Table 7. Summary of Number of QA Samples Analyzed

Measurement	Field Duplicates	Laboratory Duplicates	Matrix spikes	Matrix Spike Duplicates	Field Blanks	Trip Blanks
<u>Pretreatment</u>						
SVOCs	5	NA	4	4	3	NA
VOCs	5	NA	11	11	3	9
TRPH	5	NA	4	4	3	NA
Moisture	5	5	NA	NA	3	NA
Particle Size Distribution	NA	1	NA	NA	NA	NA
<u>Post-treatment</u>						
SVOCs	4	NA	3	3	3	NA
VOCs	4	NA	7	7	3	5
T R P H	4	NA	3	3	3	NA
Moisture	4	5	NA	NA	3	NA
Particle Size Distribution	NA	NA	NA	NA	NA	NA

NA Not analyzed

Table 8. Number of Soil Samples Taken During the SITE Demonstration

Measurement	Total	Inside Revised		Outside Revised				
		Design	Treatment	Inside	Heated	Design	Treatment	Outside
		Zone	Zone	Zone	Zone	Zone	Zone	Zone
<u>Pretreatment</u>								
SVOCs	48	31		8		17		40
VOCs	48	31		8		17		40
TRPH	48	31		8		17		40
Moisture	48	31		8		17		40
Particle Size Distribution	43^a	29		8		14		35
<u>Post-treatment</u>								
SVOCs	37	28		6		9		31
VOCs	37	28		6		9		31
TRPH	37	28		6		9		31
Moisture	37	28		6		9		31
Particle Size Distribution	11^b	9		4		2		7

^a Seven of the samples were subjected to both dry- and wet-sieving; six of the samples were subjected to wet-sieving only; the remainder of the samples were subjected to dry-sieving only.

^b All samples were subjected to the wet-sieving analysis.

Table 9. Numbers of Complete Matched Pairs for the Soil Samples

Contaminant	Inside Revised	Design	Inside Heated	Outside Revised	Outside Heated
	Treatment	Zone	Zone	Treatment	Zone
TRPH	23		5	8	2 6
Chlorobenzene	26		5	7	28
2-hexanone	5		0	1	6
4-methyl-2-pentanone	9		0	1	10
Acetone	20		4	3	19
Methyl ethyl ketone	15		2	1	14
Pyrene	7		2	3	8
Bis(2-ethylhexyl)-phthalate	17		4	6	19

4.2.2 Groundwater Sampling

Groundwater sampling was not a part of the original project scope. However, because ketones were discovered in post-treatment samples of the revised design treatment zone, groundwater samples were collected at Site S-1 approximately 6 months after post-treatment soil sampling. Post-treatment groundwater samples were collected from three wells (see Figure 6) near the treatment zone (MW-10, MW-09, and DW-02) on January 14 to 19, 1993. Three well volumes were purged from each well before the samples were collected with a Teflon^R bailer. Groundwater samples were analyzed for the same compounds as the soil samples (TRPH, VOCs, and SVOCs). Data from these samples were used to characterize the groundwater and to identify whether it was a potential source for contaminant migration into the revised design treatment zone.

4.2.3 SVE Vapor Stream Sampling

Concentrations of TRPH and specific VOCs and SVOCs in the SVE vapor stream were monitored by a USAF subcontractor and were not part of the SITE demonstration. Therefore, the appropriateness of the methods used and the quality of the data are unknown. The results appear to indicate qualitatively removals of TRPH and certain VOCs and SVOCs. Because of limitations of the sampling and analytical methods, the quantity of contaminants removed cannot be estimated.

4.3 PERFORMANCE DATA

The results presented in this subsection address primary and secondary objectives of the IITRI SITE demonstration. The primary objective of the demonstration was to measure changes in the concentrations of TRPH, selected SVOCs, and selected VOCs in the in situ soil. The critical and noncritical contaminants were discussed in Subsection 4.1.

Since the revised design treatment zone was not isolated by a physical or pneumatic barrier during the SITE demonstration, contaminant migration entering and exiting the revised design zone was a concern and, therefore, evaluated in this subsection. In order to determine if contaminant migration occurred, samples were collected and analyzed in the zone being heated and the surrounding area before and after RFH. Results of the soil sampling for each zone are summarized in Appendix A.

4.3.1 Results of Chemical Analyses

4.3.1.1 Revised Design Treatment Zone

There was a statistically significant decrease in TRPH concentration at the 95 percent confidence level; the estimated decrease in the mean concentration was 60 percent. There were statistically significant decreases in the concentrations of two SVOCs, pyrene and bis(2-ethylhexyl)phthalate, at the 97.5 percent confidence level; estimated decreases in the mean concentrations were 87 and 48 percent, respectively.

The decrease in TRPH and SVOC concentrations may be due to some combination of the RF energy and the SVE system. In areas where significant heating occurred, the contaminants were likely volatilized and migrated laterally to areas beyond the revised design treatment zone post-treatment sampling locations. Here they were either extracted by the SVE system or recondensed in the cooler soils. In cooler areas, the SVE system alone may have removed more volatile fractions of the TRPH, but removals of pyrene and bis(2-ethylhexyl)phthalate are less likely. Alternatively, these contaminants may have been pyrolytically degraded due to soil temperatures of 1,300°C (2,372°F) and greater in some areas.

Based on results of an air flow model, inefficiencies in the design of the SVE system may have resulted in gas flows between the outer edge of the impermeable cap and the extraction wells being five times greater than those between the two rows of extraction wells. As a result, contaminant migration into the treatment zone was possible, especially near the outer edges, and contaminant removal from the treatment zone may have been relatively slow as compared to inward contaminant migration. The air flow model does not indicate any pathway by which contaminants would migrate outward from inside the revised design treatment zone. The air flow model does, however, indicate pathways by which contaminants outside the revised design treatment zone could migrate toward the extraction wells. Therefore, the decreases in TRPH and SVOC concentrations are not likely due to outward migration, since the configuration of the SVE system limited this type of migration. A tracer test was performed by the developer to evaluate contaminant migration. The results of this test also indicated that inward, and not outward, migration occurred.

The air flow model does not, however, account for the generation of steam in the heated zone. The generation of steam can increase the pressure within the heated zone, causing contaminants to migrate

outward. Theoretically, the steam generation rate increases as the soil temperature increases, then decreases when most of the soil moisture has been driven off. The effect of this phenomenon has not been quantified.

For the VOCs within the revised design treatment zone, there was no statistically significant decrease in the concentration of chlorobenzene at the 90 percent confidence level. There were statistically significant increases in the concentrations of four noncritical VOCs (all ketones) at the 99 percent confidence level; estimated increases in the mean concentrations were 457 percent for 2-hexanone; 263 percent for 4-methyl-2-pentanone; 1,073 percent for acetone; and 683 percent for methyl ethyl ketone.

The fact that chlorobenzene (a VOC) did not exhibit a statistically significant decrease in the revised design treatment zone, while less volatile contaminants (i.e., pyrene) did, is difficult to explain. It is possible inward migration offset any contaminant removals. Also, the apparent removal of pyrene may be somewhat misleading since, as discussed previously, the decrease in pyrene concentration may have been due to degradation. No definitive conclusions can be drawn.

The ketones may have been formed by the degradation of TRPH near the exciter electrodes, where soil temperatures were highest. A possible degradation pathway may be the pyrolytic conversion of TRPH to unsaturated hydrocarbons. In the presence of sufficient oxygen and a catalyst (e.g., silica in the soil), the RF energy may convert these hydrocarbons into ketones. No literature was found on this exact topic, but similar reactions are described in several references [1,2]. The increase in ketones may also have been caused by inward migration. Possible sources of ketones are the groundwater, of which only post-treatment samples were taken, and the soil beyond the sampled area. However, since these sources cannot be verified, there are not sufficient data to confirm or disprove either of these hypotheses.

4.3.1.2 Heated Zone Results

There was a statistically significant decrease in TRPH concentration at the 97.5 percent confidence level; the estimated decrease in the mean concentration was 95 percent. No SVOCs or VOCs exhibited statistically significant decreases in the heated zone. Pyrene and bis(2-ethylhexyl)phthalate concentrations exhibited statistically significant decreases inside the revised design treatment zone, but not inside the heated zone. This is due to the limited number of complete matched pairs of pyrene and bis(2-ethylhexyl)phthalate data within the heated zone. Bis(2-ethylhexyl)phthalate, for example, had only four complete matched pairs of data within the heated zone. Pretreatment concentrations in all four pairs

were higher than post-treatment concentrations, but these data were not sufficient to demonstrate a decrease at the 90 percent confidence level. The number of complete matched pairs in the heated zone was also limited (less than or equal to four) for the ketones, so that no statistically significant conclusions can be drawn.

No plausible theories have been developed to explain the fact that chlorobenzene did not exhibit a statistically significant decrease in the heated zone while other less volatile contaminants such as TRPH did. The air flow model does not indicate any pathways by which contaminants can migrate into the heated zone. Furthermore, there are no apparent reaction pathways by which chlorobenzene could have been formed from other contaminants present in the soil.

4.3.1.3 Outside Revised Design Zone

Outside of the revised design treatment zone, only TRPH showed a statistically significant change at the 95 percent confidence level, with an estimated 88 percent mean concentration increase. As was previously discussed, based on the configuration of the SVE system, this increase may have been due to inward migration from the groundwater or from soil beyond the areas sampled and not outward migration from the revised design treatment zone.

4.3.1.4 Outside Heated Zone

There was a statistically significant decrease in the concentration of bis(2-ethylhexyl)phthalate at the 90 percent confidence level outside the heated zone; the estimated decrease in the mean concentration was 37 percent. There were also statistically significant increases at the 99 percent confidence level in the concentrations of four noncritical VOCs (all ketones) outside the heated zone. The estimated mean increases for these four ketones were 423 percent for 2-hexanone; 249 percent for 4-methyl-2-pentanone; 1,347 percent for acetone; and 1,049 percent for methyl ethyl ketone. As previously explained, these ketones may have been formed by the pyrolytic conversion of TRRH to unsaturated hydrocarbons, migrated inward, or have come from the groundwater.

4.3.1.5 Groundwater Samples

One groundwater sample was collected by a USAF contractor, but it is not known where or how this sample was collected. The sample was also analyzed by a USAF contractor. These analyses were not part of the SITE demonstration and the quality of the data is unknown. The laboratory report

indicates that SVOC concentrations were determined using Method 8270 from SW-846 [3] and that VOC concentrations were determined using Method 8020 from SW-846 [3]. No SVOC concentrations above detection limits were reported. VOC concentrations reported above detection limits are presented in Appendix A.

Post-treatment ketone concentrations in the soil were significantly higher than pretreatment concentrations, and the groundwater was proposed as a possible source of ketones. As stated above, the groundwater analysis conducted by a USAF contractor used Method 8020. Ketones are not on the target list for this method. To investigate the possibility of ketones in the groundwater, three groundwater samples were collected by the SITE Program. These samples were collected from three wells (MW10, MW09, and DW02) whose locations are shown in Figure 6. However, due to contractual limitations, these samples were collected approximately 5 months after post-treatment sampling. As a result, it is not known whether these samples are representative of groundwater contaminant concentrations during the demonstration. Ketones were detected at low concentrations in one of the three samples. The results of these samples are presented in Appendix A.

4.3.1.6 Condensate Samples

Condensate from the vapor treatment system was collected in a 55-gallon (0.21-cubic-meter) drum. When the drum became full or nearly full, its contents were pumped to a 20,000-gallon (76-cubic-meter) tank used to store water from dewatering activities. The combined water was subsequently transferred to a Kelly AFB facility for treatment. The total quantity of condensate was not measured, but the date, time, and approximate quantity were recorded in a field log each time the condensate drum was emptied. Based on this information, it is estimated that 800 gallons (3 cubic meters) of condensate were collected.

Two condensate samples were collected by a USAF contractor on May 14, 1993. The condensate samples were analyzed by a USAF contractor. These analyses were not part of the SITE demonstration and the quality of the data is unknown. The laboratory report indicates that SVOC concentrations were determined using Methods 3510 and 8270 from SW-846 [3]; VOC concentrations were determined using Methods 5030 and 8260 from SW-846 [3]; and TRPH was determined using EPA Method 418.1 [4]. Concentrations reported above detection limits are presented in Appendix A.

4.3.1.7 SVE Vapor Stream

Concentrations of TRPH and specific VOCs and SVOCs in the SVE vapor stream were monitored by a USAF contractor and were not part of the SITE demonstration. The results appear to indicate qualitatively removals of TRPH and certain VOCs and SVOCs but no conclusions can be drawn, since the appropriateness of the methods used and the quality of the data are unknown. Graphs of the vapor stream data for selected contaminants are presented in Appendix A.

4.3.1.8 Moisture

Moisture analysis was conducted so that soil sample concentration results could be converted to dry weight. Appendix A presents the results of moisture analyses.

4.3.2 Physical Analyses

4.3.2.1 Particle Size Distribution

Particle size distribution analyses were conducted to characterize the soil. For evaluation purposes, particle size distribution data are simplified into three categories: gravel, sand, and fines. Particles that are less than 3 inches (0.08 meters) in diameter but will not pass through a #4 sieve (4.750 millimeters) are classified as gravel, particles that will pass through a #4 sieve (4.750 millimeters) but will not pass through a #200 sieve (0.075 millimeters) are classified as sand, and particles that will pass through a #200 sieve (0.075 millimeters) are classified as fines.

Pretreatment particle size distribution analyses were conducted using two procedures, which are referred to as dry-sieving and wet-sieving. Regardless of which procedure was used to analyze the samples, the soils were first prepared according to American Society for Testing and Materials (ASTM) Method D421 [5]. In this method, the soils are dried and processed to break down all soil particles into their component sizes. The samples that were dry-sieved were simply taken from the sample preparation procedure and screened using 12 sieve sizes, ranging from 3 inches (0.08 meters) to #200 sieve (0.075 millimeters). This procedure was used as an inexpensive way to characterize a large number of soil samples at the site. The wet-sieving procedure followed ASTM Method D422 [5]. This method was used to confirm the dry-sieving results and was expected to yield similar results. For each of the wet-sieved samples, the dried soil sample is initially segregated into two fractions using a #10 sieve (2.00 millimeters). Soils that pass through the #10 sieve (2.00 millimeters) are then dispersed in an aqueous solution and passed over the remaining sieves "wet." Particles that pass through the #200 sieve (0.075

millimeters) are further classified using a hydrometer, which results in a minimum size classification of approximately 0.001 millimeters.

Most pretreatment samples were analyzed by dry-sieving only, but a fraction of the samples were analyzed by wet-sieving only or by both wet- and dry-sieving. (Because only 11 post-treatment samples were collected for particle size distribution analyses, they were all analyzed by wet-sieving.) Wet- and dry-sieving were used in combination because discussions with laboratory personnel indicated that the two procedures would yield similar results for particles that would not pass through a #200 sieve (0.075 millimeters). It was known that wet-sieving and a subsequent hydrometer analysis would be required to characterize further particles that would pass through a #200 sieve (0.075 millimeters). Since dry-sieving is less costly, and the further characterization of these small particles was a minor point, it seemed reasonable to use dry-sieving primarily.

Contrary to expectations, wet-sieving produced significantly different results from dry-sieving. It appears that the sample preparation associated with the dry-sieved samples was not rigorous enough to break down many of the cohesive silt and clay particles into sixes that would pass through a #200 sieve (0.075 millimeters).

For evaluation purposes, particle size distribution data are simplified into three categories: gravel, sand, and fines. Particles that will not pass through a #4 sieve (4.750 millimeters) are classified as gravel, particles that will pass through a #4 sieve (4.750 millimeters) but will not pass through a #200 sieve (0.075 millimeters) are classified as sand, and particles that will pass through a #200 sieve (0.075 millimeters) are classified as fines.

The dry-sieving results should accurately represent the fraction of gravel present at the site, but probably do not accurately represent the fractions of sand and fines. The actual fraction of sand is likely to be lower than the dry-sieving results indicate, and the fraction of fines correspondingly higher. Dry-sieving results should, therefore, only be used to characterize the site in terms of the fraction of gravel and the fraction of sand and fines. Wet-sieving results should be used to characterize the site in terms of the individual fractions of sand and fines. Table 6 summarizes the number of particle size distribution samples taken during the demonstration. The particle size distribution results are summarized in Table 10. The results of each particle size sample are presented in Appendix A.

Table 10. Summary of Particle Size Distribution Data

Dry-Sieving	96 Gravel	96 Sand, Clay, and Silt
Pretreatment	42.6	57.4
Wet-Sieving	% Gravel	% Sand
Pretreatment	38.8	25.5
Post-treatment	44.1	33.9
		% Fines
		35.8
		22

4.4 RESIDUALS

The aqueous residuals generated during the RFH SITE demonstration included groundwater from the dewatering wells and washwater from PPE and equipment decontamination. During the demonstration, 325,920 gallons (1,234 cubic meters) of groundwater were removed from the soil, stored in 20,000-gallon (76-cubit-meter) tanks and periodically transferred to a Kelly AFB facility for treatment.

Depending on its design, the vapor treatment system may generate residuals. The materials handling requirements for these residuals vary depending on the design of the vapor treatment system and the contaminants present in the soil. During the SITE demonstration, condensate that formed in the vapor collection system was collected in a 55-gallon (0.21-cubic-meter) drums. Approximately 800 gallons (3 cubic meters) of condensate were collected, pumped to the groundwater storage tank, transferred to a Kelly AFB facility, and treated with the groundwater from the dewatering wells. Uncondensed vapors were channeled directly to a propane-fueled flare. The quantity of uncondensed vapors was not measured, but operating conditions for the SVE system were monitored by a USAF contractor and are summarized in Appendix A, Subsection A.3.2.

Two drums of spent carbon, used during the demonstration for shield air evacuation, were generated. The spent carbon was analyzed and found to be nonhazardous. The vendor planned on regenerating the carbon for reuse.

4.5 REFERENCES

1. Scheffer, J.R. and M.D. Ouchi, Tetrahedron Letters, 3, 233, 1970.
2. House, H.O., Modern Synthetic Reactions, Second Edition, pp. 338-340, 1972
3. U.S. Environmental Protection Agency, Test Methods for Evaluating Solid Waste (SW-846): Third Edition, November, 1986, and Final Update, September, 1990.
4. U.S. Environmental Protection Agency, EPA Methods for Chemical Analysis of Water and Wastes, 1983.
5. American Society for Testing and Materials (ASTM), Annual Book of ASTM Standards

SECTION 5

OTHER TECHNOLOGY REQUIREMENTS

5.1 ENVIRONMENTAL REGULATION REQUIREMENTS

State regulatory agencies may require permits for the onsite installation and operation of IITRI's RFH system. An air emissions permit may be required for the vapor treatment system. If offsite disposal of contaminated residuals is required, the residuals must be removed from the site by a licensed transporter. These residuals must be treated or disposed of by a permitted incinerator or other treatment or disposal facility.

5.2 PERSONNEL ISSUES

Appropriate PPE should be available and properly utilized by all onsite personnel. PPE requirements are site-specific and should be determined based on the contaminants present at the site and on the work activities being conducted. During the demonstration, PPE levels were designated according to the potential hazards associated with each work activity. At a minimum, Level D PPE was required for all personnel within the exclusion zone. During most demonstration activities, site personnel were not in contact with the contaminated soil because it was covered with a layer of gravel. The potential for exposure to soil contaminants was increased during drilling activities, including pretreatment sampling, installation of subsurface system components, and post-treatment sampling,

Site monitoring should be conducted to identify the extent of hazards and to document exposures at the site. Monitoring results should be maintained and posted. During the demonstration, a hand-held FID was used to monitor the air near the surface and in the breathing zone during drilling and related activities. Because the degree of soil contamination varied considerably within the treatment zone, the drill crew and other personnel working near the borehole alternated use of Level C and Level D PPE. The drill crew upgraded to Level C when the FID indicated air contaminant concentrations in the breathing zone were greater than 5 ppm over background for 5 minutes and were permitted to downgrade to Level D when the FID indicated breathing zone air contaminant concentrations were maintained at less than 5 ppm over background. Respirators were required periodically during pretreatment as well as on several occasions during post-treatment sampling activities.

OSHA 40-hour training covering PPE application, safety and health, and emergency response procedures should be required for all personnel working with the RFH technology. Additional training provided prior to the operation of the system at a given site should include information regarding emergency evacuation procedures; safety equipment locations; the boundaries of the exclusion zone, contaminant reduction zone, and support zone; PPE requirements; and site- and technology-specific hazards. Potential hazards associated with the RFH technology include drilling accidents and personnel exposure to RF fields. Safe operating procedures should always be observed, particularly during drilling operations. Periodic monitoring for RF fields and the use of the system's RF shield will also reduce the technology-specific hazards.

Onsite personnel should participate in a medical monitoring program. Health and safety monitoring and incident reports should be routinely filed, and records of occupational illnesses and injuries (OSHA Forms 102 and 200) should be maintained. Audits ensuring compliance with the health and safety plan should be carried out. In the event of an accident, illness, hazardous situation at the site, or intentional act of harm, assistance should be immediately sought from the local emergency response teams and first aid or decontamination should be employed when appropriate. To ensure a timely response in case of an emergency, workers should review the evacuation plan, firefighting procedures, cardiopulmonary resuscitation (CPR) techniques, and emergency decontamination procedures before operating the system. An evacuation vehicle should be available at all times.

5.3 COMMUNITY ACCEPTANCE

Community acceptance of a technology is affected by both actual and perceived hazards. The fact that the RFH technology allows in situ remediation of contaminated soils should improve the potential for community acceptance, since excavation of contaminated soils often releases volatile contaminants. Although some contaminants will likely be released during electrode and thermowell installation, the potential for emissions during drilling is substantially lower than during excavation.

Disadvantages associated with in situ RFH and other in situ technologies are the difficulty of determining whether the treatment zone has been uniformly remediated and the potential for contaminant migration if pockets of contamination remain in the soil. Actual or perceived hazards associated with the RF energy may also become an issue, as potential health effects of electromagnetic fields have recently received significant publicity. The American Conference of Government and Industrial Hygienists (ACGIH) has established Threshold Limit Values (TLVs) for RF radiation. The TLVs are dependent on

the frequencies of the radio waves. TLVs and formulas for calculating TLVs are presented in Table 10. The RFH system used during the SITE demonstration was designed to operate at a primary frequency of 6.78 MHz and a secondary frequency of 3.4 MHz. TLVs for these specific frequencies are also presented in Table 11.

Table 11. Radio Frequency Radiation TLVs [1]

Frequency	Power Density ^b (mW/cm ²)	Electric Field Strength ^b (V/m)	Magnetic Field Strength ^b (A/m)
6.78 MHz		541.8	4.79
30 kHz to 100 kHz		271.7	2.40
100kHz to 3MHz		614	163
3 MHz to 30MHz		614	16.3/f
30 MHz to 100 MHz		1842/f	16.3/f
100MHz to 300MHz	1	61.4	16.3/f
300 MHz to 3 GHz	f/300	61.4	0.163
3 GHz to 15 GHz	10		
15GHz to 300GHz	10		

a The exposure values in terms of electric and magnetic field strengths are the values obtained by spatially averaging values over an area equivalent to the vertical cross-section of the human body projected area). The exposure values for 30 kHz to 15 GHz are calculated by averaging the values over 6 minutes.

b f = frequency in MHz

5.4 REFERENCES

1. American Conference of Government and Industrial Hygienists. Threshold Limit Value. 1992.

SECTION 6

TECHNOLOGY STATUS

IITRI's RFH system was used to heat approximately 125 cubic yards (95.6 cubic meters) of soil in the revised design treatment zone at Site S-1 at Kelly AFB during the SITE demonstration. However, due to the presence of a shallow groundwater table that previous geological studies had not indicated and operational problems during the demonstration, only a portion of the revised design zone was heated to the desired temperature of 150°C (302°F). This zone is referred to as the "heated zone." The soil was contaminated with mixed solvents, carbon cleaning compounds, and petroleum oils and lubricants. The results of this demonstration are discussed in Section 4 and Appendix A of this document.

Prior to the SITE demonstration, IITRI's RFH system was tested at two other sites: RMA and Volk ANGB. At RMA, approximately 60 cubic yards (50 cubic meters) were contaminated with wastes from chemical warfare agents, incendiary and explosive munitions, pesticides, and herbicides. At Volk ANGB approximately 20 cubic yards (15 cubic meters) of soil were contaminated with organics including waste oils, fuels, and solvents. Both tests are discussed in greater detail in Appendix B.

IITRI claims its technology is not ready for commercialization. Considerable development and optimization of the process is required before a full-scale system is ready for field use. The IITRI RFH technology cannot be used as a stand-alone technology.

APPENDIX A

SUPPLEMENTARY DATA

A.1 CHEMICAL ANALYSES

A.1.1 Procedure for Selecting Contaminants for Statistical Evaluation

Soil samples were analyzed for TRPH and target VOCs and SVOCs. The target VOCs (those in Method 8240) are listed in Table A-1; the target SVOCs (those in Method 8270) are listed in Table A-2. Critical contaminants were selected from these lists of analytes based on a combination of the following:

- Pretreatment concentration information provided by B&RE
- Data from SAIC's pretreatment soil sampling

All critical contaminants were selected for a preliminary statistical evaluation (Subsection A. 1.2). TRPH, five SVOCs (2-methylnaphthalene; naphthalene; 1,2-dichlorobenzene; 1,3-dichlorobenzene; and 1,4-dichlorobenzene), and five VOCs (benzene, toluene, ethylbenzene, chlorobenzene, and xylenes) were designated as critical.

The only noncritical SVOCs that were subjected to a preliminary statistical evaluation were those with concentrations above their method detection limit (MDL) in at least 25 pretreatment soil samples. Pyrene and bis(2-ethylhexyl)phthalate were the only noncritical SVOCs to meet the qualifications to undergo a preliminary statistical evaluation. The only noncritical VOCs that were subjected to a preliminary statistical evaluation were: 2-hexanone, 4-methyl-2-pentanone, methyl ethyl ketone, and acetone. These contaminants were chosen since they were present in much larger quantities in the post-treatment samples than in the pretreatment samples.

All contaminants that showed a statistically significant change in the preliminary evaluation were then subjected to a final evaluation (Subsection A.3.2).

Table A-1. Target VOCs in the Initial and Final Soil Samples*

Compounds	Classification
Acetone	NC
Benzene	C
Bromodichloromethane	NC
Bromoform	NC
Bromomethane	NC
2-Butanone (methyl ethyl ketone)	NC
Carbon disulfide	NC
Carbon tetrachloride	NC
Chlorobenzene	C
Chlorodibromomethane	NC
Chloroethane	NC
2-Chloroethyl vinyl ether	NC
Chloroform	NC
Chloromethane	NC
1, 1-Dichloroethane	NC
1,2-Dichloroethane	NC
1 , 1-Dicbloroethene	NC
trans-1 ,2-Dichloroethene	NC
1,2-Dichloropropane	NC
cis-1,3-Dichloropropane	NC
trans-1,3-Dichloropropene	NC
Ethylbenzene	C
2-Hexanone	NC
Methylene chloride	NC
4-Methyl-2-pentanone	NC

C Critical

NC Noncritical

* Extracted by Method 3540 and analyzed by Method 8240.

Table A-1. Target VOCs in the Initial and Final Soil Samples* (Continued)

Compounds	Classification
Styrene	NC
Toluene	C
1,1,2-Trichloroethane	NC
Trichloroethene	NC
Vinyl acetate	NC
Vinyl chloride	NC
Xylenes (total, all isomers)	C

C Critical

NC Noncritical

* Extracted by Method 3540 and analyzed by Method 8240.

Table A-2. Target SVOCs In the Initial and Final Soil Samples*

Compounds	Classification
Base/Neutral Extractables	
Acenaphthene	NC
Acenaphthylene	NC
Anthracene	NC
Benzo(a)anthracene	NC
Benzo(b)fluoranthene	NC
Benzo(k)fluoranthene	NC
Benzo(ghi)perylene	NC
Benzo(a)pyrene	NC
Benzyl alcohol	NC
bis(2-Chloroethoxy)methane	NC
bis(2-Chloroethyl)ether	NC
bis(2-Chloroisopropyl)ether	NC
Bis(2-ethylhexyl)phthalate	NC
4-Bromophenylphenylether	NC
Butylbenzylphthalate	NC
4-Chloroaniline	NC
2-Chloronaphthalene	NC
4-Chlorophenyl phenyl ether	NC
Chrysene	NC
Dibenz(a,h)anthracene	NC
Dibenzofuran	NC
Di-n-butylphthalate	NC
1,2-Dichlorobenzene	C
1,3-Dichlorobenzene	C
1,4-Dichlorobenzene	C
3,3'-Dichlorobenzidine	NC
Diethylphthalate	NC
Dimethylphthalate	NC
2,4-Dinitrotoluene	NC
2,6-Dinitrotoluene	NC
Di-n-octylphthalate	NC
Fluoranthene	NC
Fluorene	NC
Hexachlorobenzene	NC

C Critical

NC Non-critical

* Extracted by Method 3540 and analyzed by Method 8270.

Table A-2. Targ SVOCs In the Initial and Fina Soil Samples* (Continued)

Compounds	
Hexachlorobutadiene	NC
Hexachlorocyclopentadiene	NC
Hexachloroethane	NC
Indeno(1,2,3-cd)pyrene	NC
Isophorone	NC
2-Methylnaphthalene	C
Naphthalene	C
2-Nitroaniline	NC
3-Nitroaniline	NC
4-Nitroaniline	NC
Nitrobenzene	NC
n-Nitrosodiphenylamine	NC
n-Nitrosodipropylamine	NC
Phenanthrene	NC
Pyrene	NC
1,2,4-Trichlorobenzene	NC
Acid Extractables	
Benzoic acid	NC
4-Chloro-3-methylphenol	NC
2-Chlorophenol	NC
2,4-Dichlorophenol	NC
2,4-Dimethylphenol	NC
4,6-Dinitro-2-methylphenol	NC
2,4-Dinitrophenol	NC
2-Methylphenol	NC
4-Methylphenol	NC
2-Nitrophenol	NC
4-Nitrophenol	NC
Pentachlorophenol	NC
Phenol	NC
2,4,5-Trichlorophenol	NC
2,4,6-Trichlorophenol	NC

C Critical

NC Non-critical

* Extracted by Method 3540 and analyzed by Method 8270.

A.1.2 Methodology for Statistical Evaluation

The test design called for paired soil samples to be collected before and after the RFH treatment. Because the test design was structured for a comparison of paired samples, pre- and post-treatment data for the revised design treatment zone were reviewed and data pairs were matched.

Practical quantitation limits (PQLs) of five times the MDLs were calculated for all data points for each of these contaminants; these PQLs were then used during the statistical analyses. The use of PQLs eliminates estimated results and yields a more conservative evaluation. Because the PQLs were defined as five times the MDLs, the conversion to PQLs eliminated many previously identified complete matched pairs. Performing statistical evaluations on the revised design treatment zone and heated zone instead of the original design treatment zone also eliminated several complete matched pairs.

Data pairs were eliminated from consideration in the statistical analysis for any one of three reasons:

1. A reported pair was dropped from the statistical analysis if both samples (pre- and post-treatment) were less than their respective PQLs.
2. A reported pair was dropped if the pair consisted of one detected value and one observation less than the PQL when the PQL was greater than the detected value (otherwise the pair was retained and the PQL value used).
3. A reported pair was dropped if one or both members of the pair were coded “NA” (that is, no sample was collected for one or both members of the pair).

The number of complete matched pairs for a given contaminant was determined and was represented by N. The distribution of the data was evaluated and was judged to be log-normal. Probability plots of the data were generated in the original scale and in the log-transformed scale, and it was visually determined that the transformed data were closer to a normal distribution. The distribution of contaminant concentrations in soil is generally highly skewed, and log-transformations are commonly done. Logarithms of all data were calculated before the data were manipulated, which is a conventional statistical practice for log-normally distributed data. X_{i0} was used to represent the pretreatment log concentration of this compound from the i^{th} sample location and X_{i1} was used to represent the post-treatment log concentration from the i^{th} sample location (where i varied from 1 to N). The difference in log concentrations ($X_{i1} - X_{i0}$) was calculated for each data pair and was denoted by d_i . The mean of the differences in log concentrations was calculated according to the following formula:

$$\bar{d} = \frac{1}{N} \sum_{i=1}^N d_i$$

R was used to represent the geometric mean of the ratios of post-treatment concentration to pretreatment concentration, which was calculated from the mean of the differences in log concentrations according to the following formula:

$$R = 10^{\bar{d}}$$

R was then converted to either percent removal or percent increase, as appropriate.

The standard deviation of the differences in log concentrations was calculated according to the following formula:

$$s = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (d_i - \bar{d})^2}$$

It was assumed that the unknown pre- and post-treatment logmean concentrations throughout the entire site were μ_0 and μ_1 , respectively, and the logvariances were equal. The following equation defines the statistic used in the paired *t* test:

$$t = \frac{\bar{d}}{s} \sqrt{N}$$

The resulting value of *t* was compared to tabulated values of *t* for two-tailed tests to determine the probability that the measured change (percent removal or percent increase) was representative of the heated zone.

Results for all critical compounds and select noncritical compounds (see Subsection A. 1.1) within the original design treatment zone were subjected to a preliminary evaluation which consisted of using a 2-sided *t* test to determine if a statistically significant concentration change was exhibited at greater than or equal to the 80 percent confidence level. The geometric mean percent change in concentration was also estimated. The eight compounds that exhibited statistically significant changes were: TRPH; bis(2-ethylhexyl)phthalate; pyrene; chlorobenzene; 2-hexanone; 4-methyl-2-pentanone; acetone; and methyl ethyl ketone.

A final statistical evaluation was then conducted on these eight contaminants for each of the four zones: the revised design treatment zone, the heated zone, outside the revised design treatment zone, and outside the heated zone. The final evaluation consisted of performing a 2-sided *t* test to determine if a statistically significant concentration change was exhibited at greater than or equal to the 90 percent confidence level. In addition, the geometric mean percent change in concentration was estimated. The upper and lower 90 percent confidence intervals were also calculated for each contaminant within the revised design treatment zone and heated zone. All of the compounds with the exception of chlorobenzene achieved a statistically significant change at the 90 percent confidence level.

A.1.3 Data Summary

A.1.3.1 Soil Samples

Figures A-1 through A-8 summarize the contaminant concentrations used in the final statistical evaluation. Each of the eight figures presents pre- and post-treatment results for one of the eight contaminants. To illustrate sampling locations, the results are presented on cross-sections of the original design treatment zone. Each figure consists of three cross-sections of the original design treatment zone. For each figure, the first cross-section shows samples collected from ground electrode row A, the second cross-section shows samples collected from exciter electrode row B, and the third cross-section shows samples collected from ground electrode row C. Samples collected from the thermowells TW1, TW2, and TW7 are included in the second cross-section because TW1 and TW2 are in line with the exciter electrodes. TW7 is actually outside the original design treatment zone entirely, but it is included in the second cross-section for convenience.

The revised design treatment zone and the heated zone are shown on the cross-sections. For each cross-section, samples included in the revised design treatment zone are inside a box formed by a thin black line. Samples included in the heated zone are inside a box formed by a thick black line. The heated zone is only shown on the second cross-section, because it does not extend out to the ground electrode rows. (Samples not included in each of these zones are outside the appropriate box.) Note that all samples included in the heated zone are also included in the revised design treatment zone. Also, note that the pretreatment samples for TW2 were outside of the heated zone but the post-treatment samples were actually inside the heated zone boundaries. For purposes of statistical evaluation, TW2 was considered outside of the heated zone.

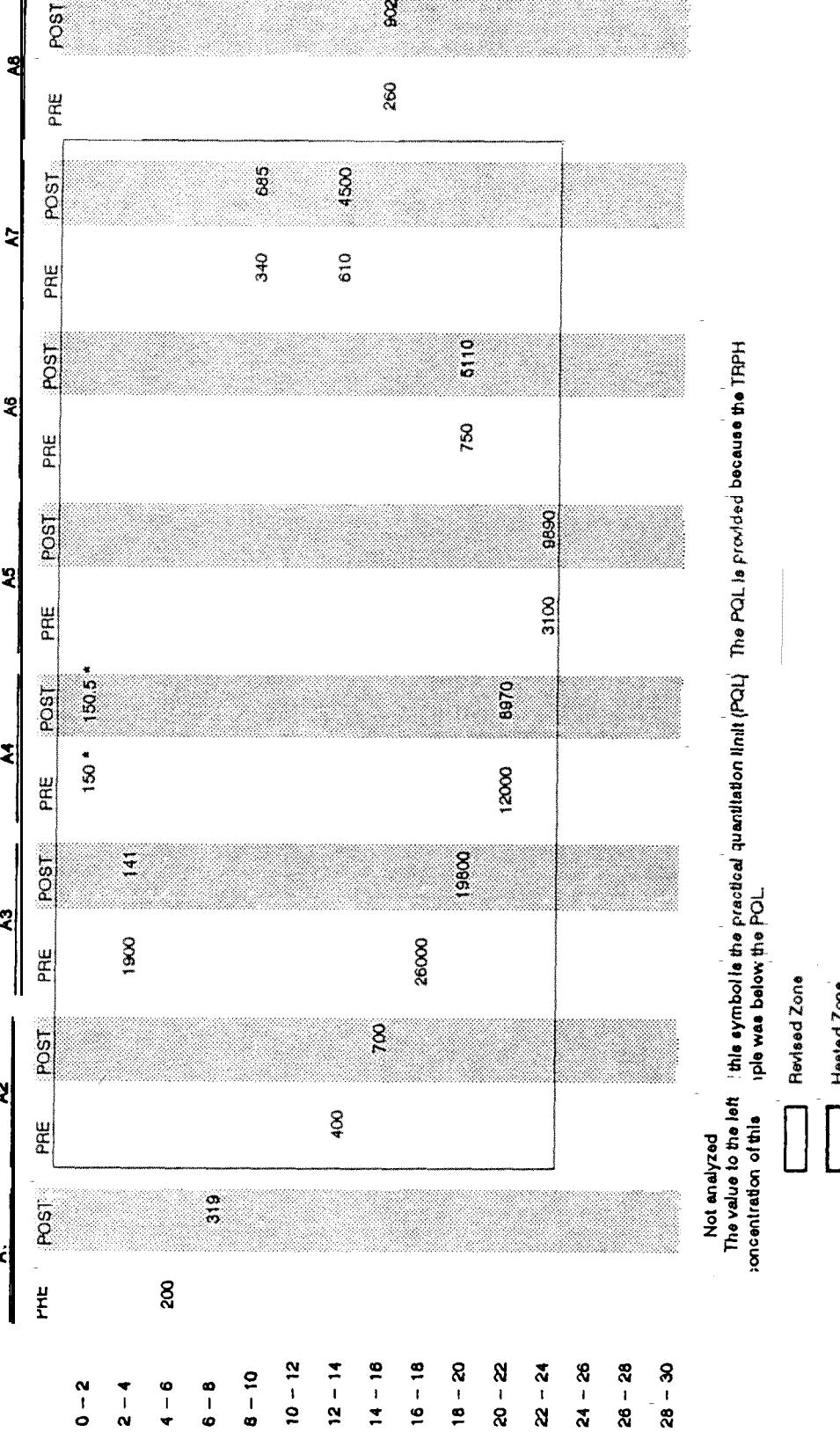


Figure A-1. IITRI soil samples: initial and final TRPH concentrations at depths of 24 feet or less, ppm.

		TW7		TW1		TW2		B1		B2		B3		B4	
		PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST
0 - 2															
2 - 4															
4 - 6		270	356	300	271	420	124*			360	124.5*				
6 - 8															
8 - 10															
10 - 12															
12 - 14															
14 - 16		9300	7030	1400	2420	980	1300			204					
16 - 18															
18 - 20															
20 - 22															
22 - 24															
24 - 26															
26 - 28															
28 - 30															

NA: Not analyzed

*: The value to the left of this symbol is the practical quantitation limit (PQL). The PQL is provided because the TAPH concentration of this sample was below the PQL.

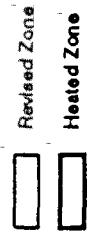


Figure A.1. IITRI soil initial and final TRPH ratios at depths of 24 feet or less, ppm

C:	C1		C2		C3		C4		C5		C6		C7		C8	
	PRE	POST														
0 - 2																
2 - 4																
4 - 6																
6 - 8																
8 - 10																
10 - 12																
12 - 14																
14 - 16																
16 - 18																
18 - 20																
20 - 22																
22 - 24																
24 - 26																
26 - 28																
28 - 30																

NA: Not analyzed

*: The value to the left of this symbol is the practical quantitation limit (PQL). The PQL is provided because the TRPH concentration of this sample was below the PQL.

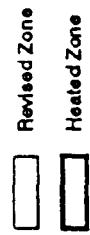
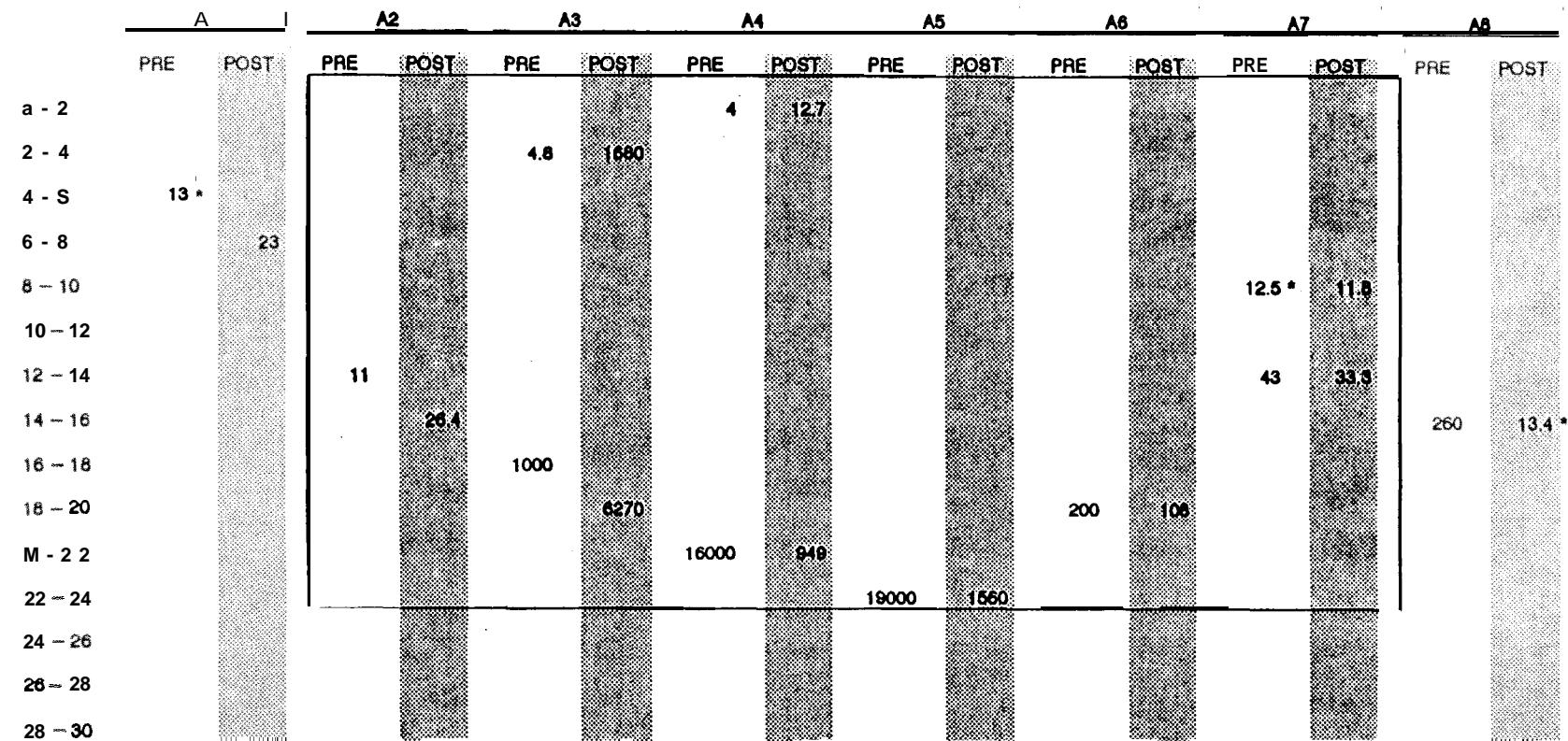


Figure A-1. IITRI soil samples: initial and final TRPH concentrations at depths of 24 feet or less, ppm (continued).



NA: Not analyzed

*: The value to the left of this symbol is the practical quantitation limit (PQL). The PQL is provided because the chlorobenzene concentration of this sample was below the PQL.

 Revised Zone

 Heated Zone

Figure A-2. ITRI soil samples initial and final chlorobenzene concentrations at depths of 24 feet or less ppb

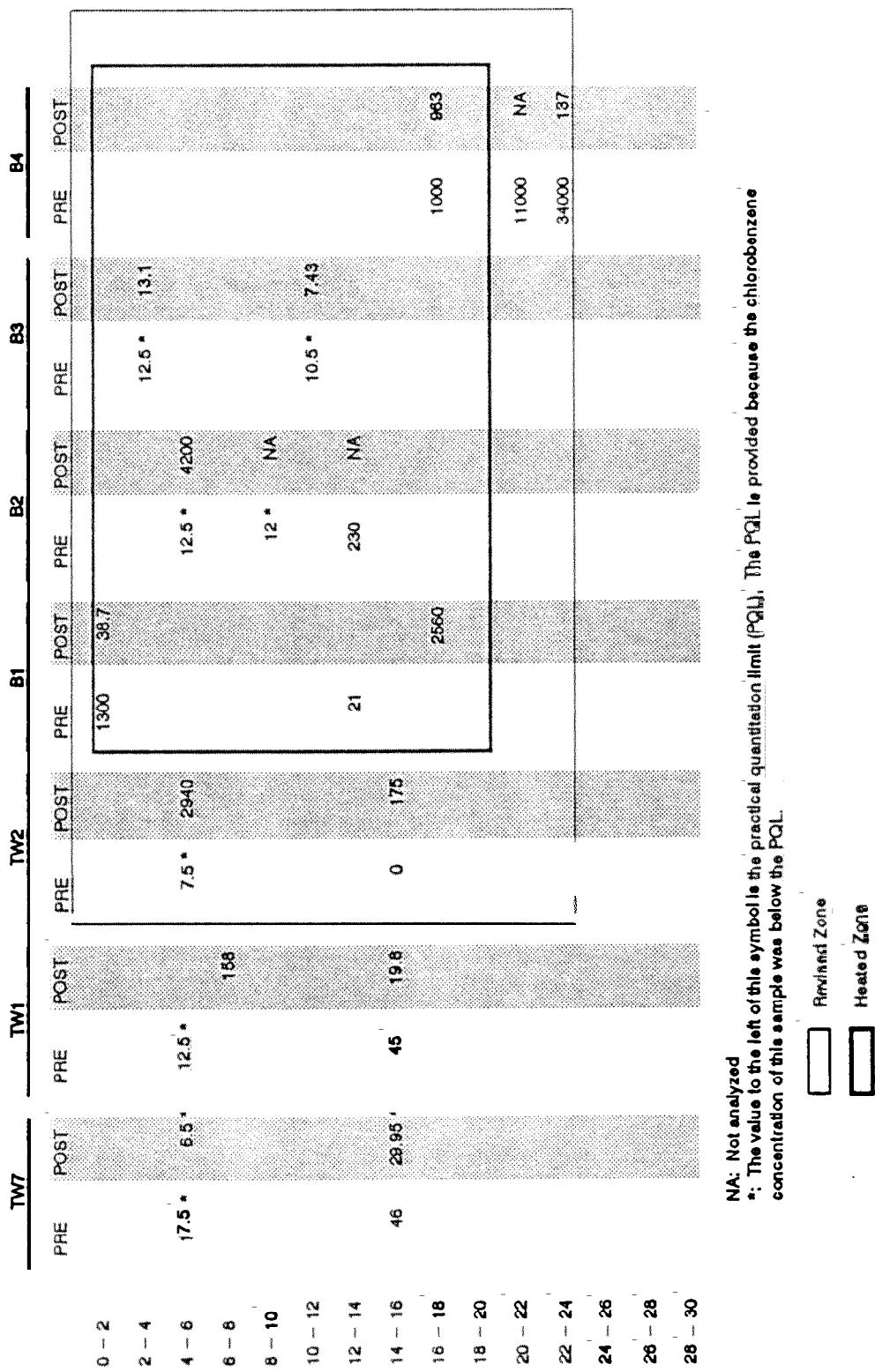


Figure A-2. HTRI soil samples: initial and final chlorobenzene concentrations at depths of 24 feet or less, ppb (contint

		C1		C2		C3		C4		C5		C6		C7		C8	
PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST
0 - 2																	
2 - 4																	
4 - 6																	
6 - 8																	
8 - 10																	
10 - 12																	
12 - 14																	
14 - 16																	
16 - 18																	
18 - 20																	
20 - 22																	
22 - 24																	
24 - 26																	
26 - 28																	
28 - 30																	

NA: Not analyzed

*: The value to the left of this symbol is the practical quantitation limit (PQL). The PQL is provided because the chlorobenzene concentration of this sample was below the PQL.

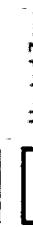


Figure A-2. IITRI soil samples: initial and final chlorobenzene concentrations at depths of 24 feet or less, ppb (continued).

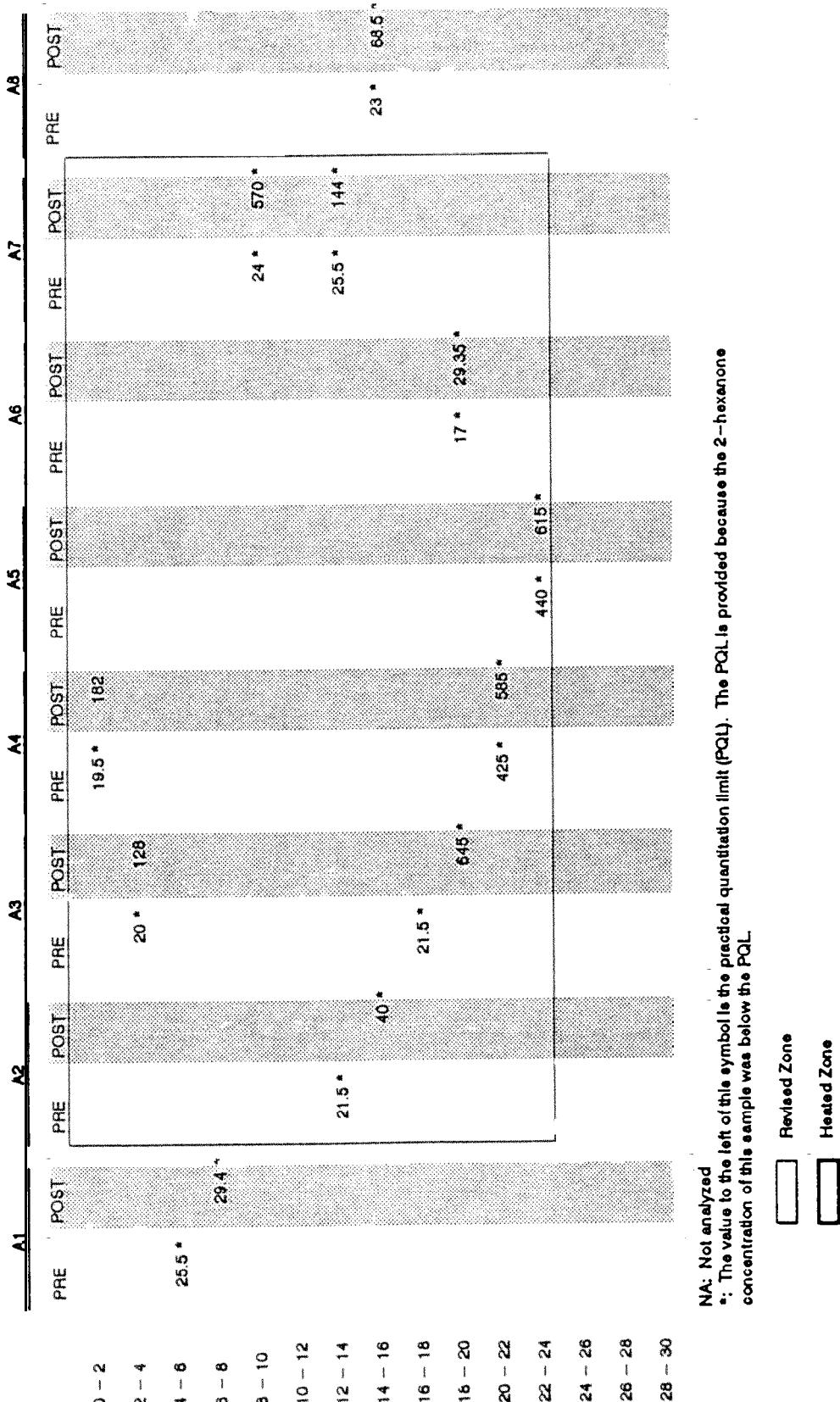


Figure A-3. IITRI soil samples: initial and final 2-hexanone concentrations at depths of 24 feet or less, ppb.

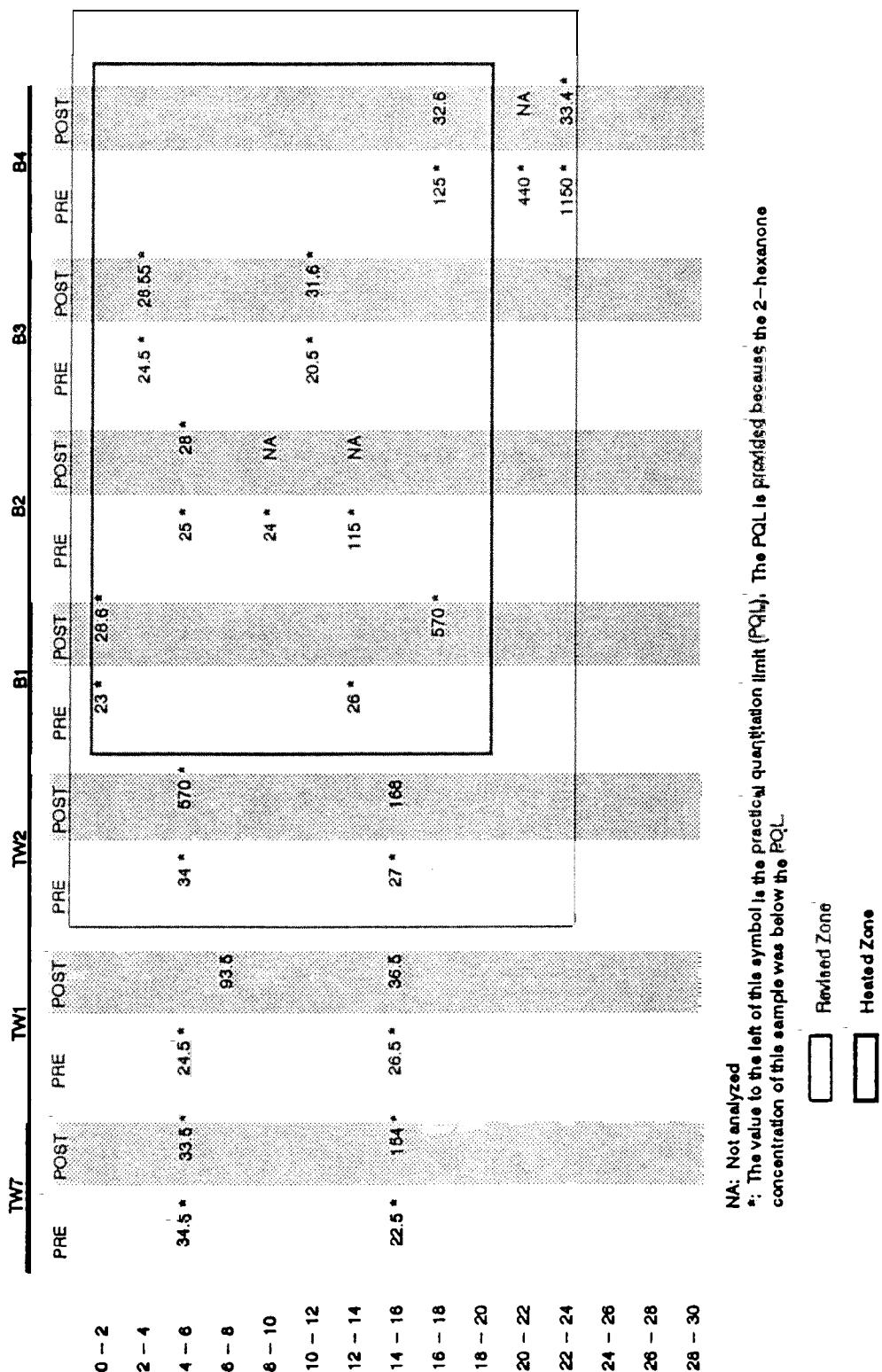


Figure A-3. IITRI soil samples: initial and final 2-hexanone concentrations at depths of 24 feet or less, ppb.

	C1		C2		C3		C4		C5		C6		C7		C8	
	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST
0 - 2					25.5 *	70.7					23 *	17.8 *				
2 - 4													24.5 *	127	25 *	18 *
4 - 6																
6 - 8					39.6 *								30.5 *			
8 - 10																
10 - 12													570 *			
12 - 14																
14 - 16																
16 - 18																
18 - 20																
20 - 22																
22 - 24																
24 - 26																
26 - 28																
28 - 30																

NA: Not analyzed
*: The value to the left of this symbol is the practical quantitation limit (PQL). The PQL is provided because the 2-hexanone concentration of this sample was below the PQL.



Figure A-3. IITRI soil samples: initial and final 2-hexanone concentrations at depths of 24 feet or less, ppb.

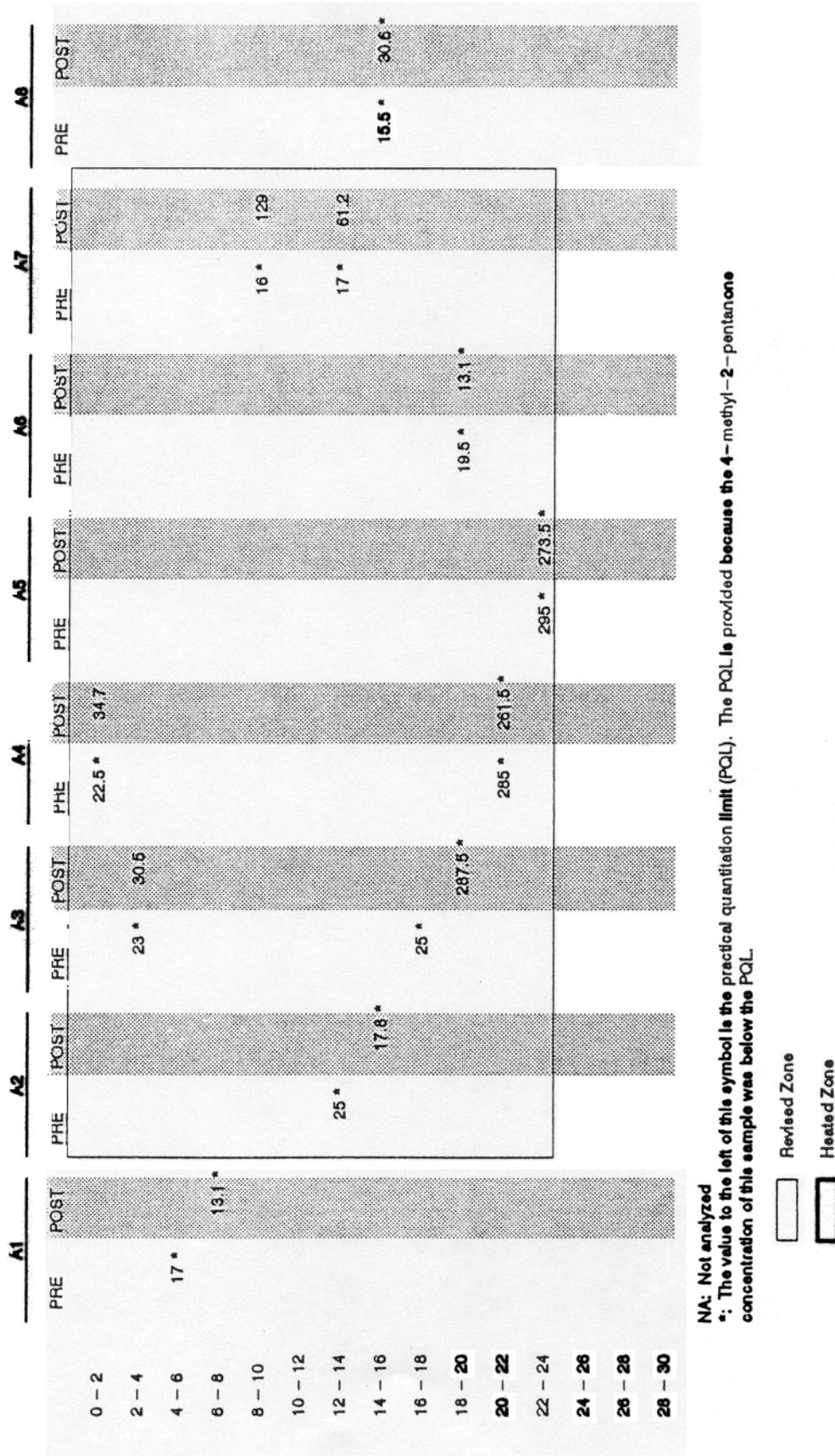


Figure A-4. IITRI soil samples: initial and final 4-methyl-2-pentanone concentrations at depths of 24 feet or less, ppb.

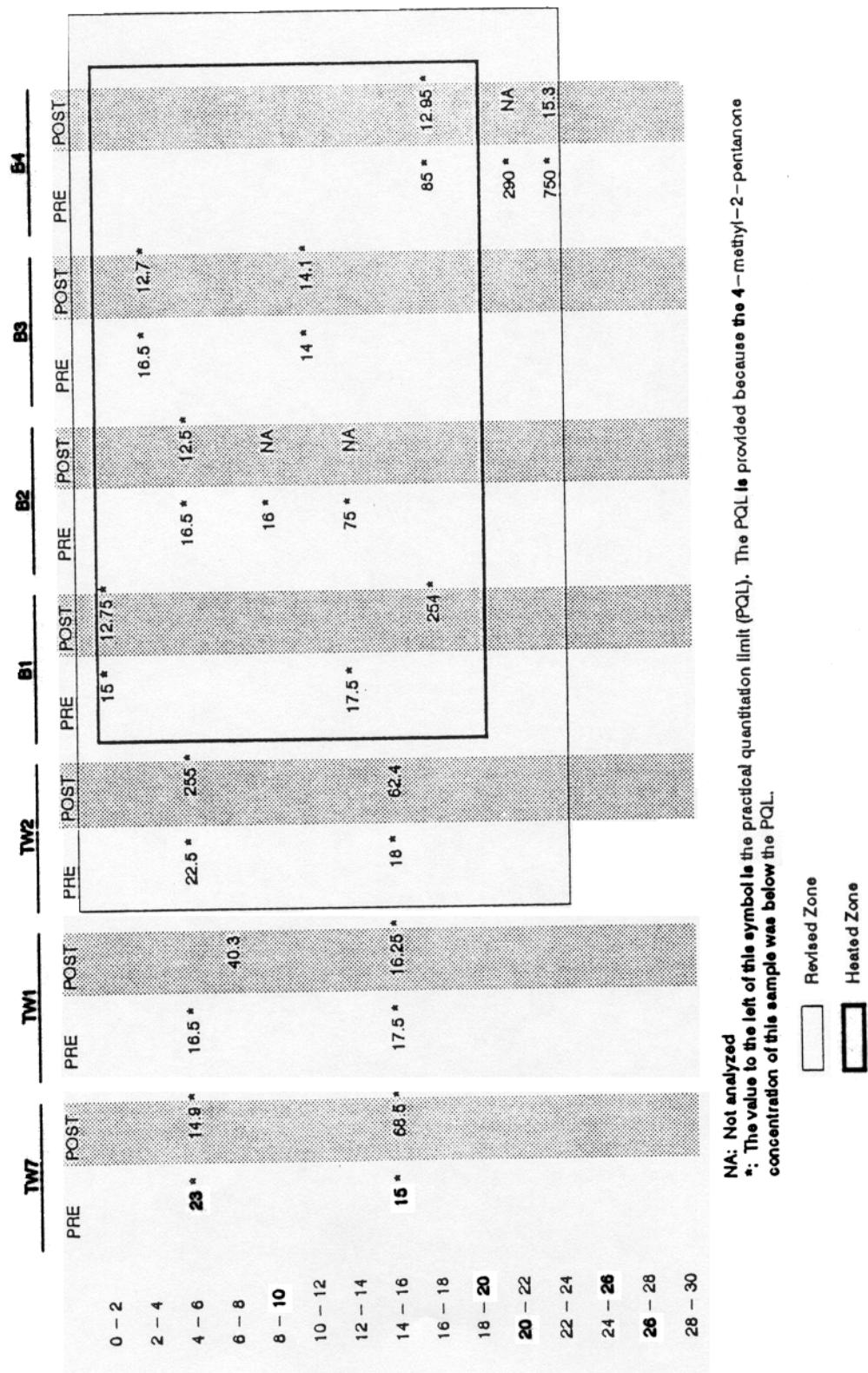
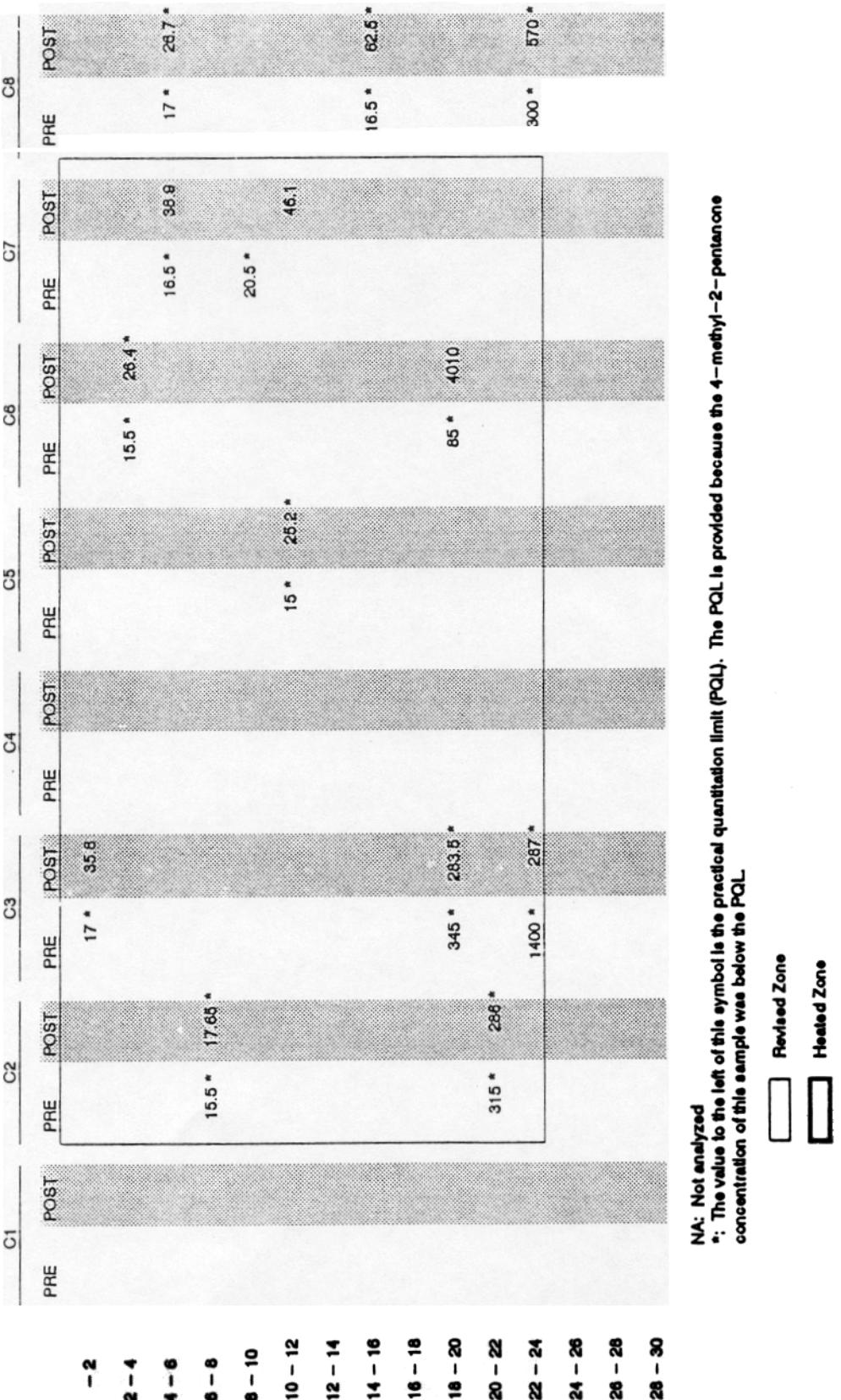


Figure A-4. IITRI soil samples: initial and final 4-methyl-2-pentanone concentrations at depths of 24 feet or less, ppb (continued).

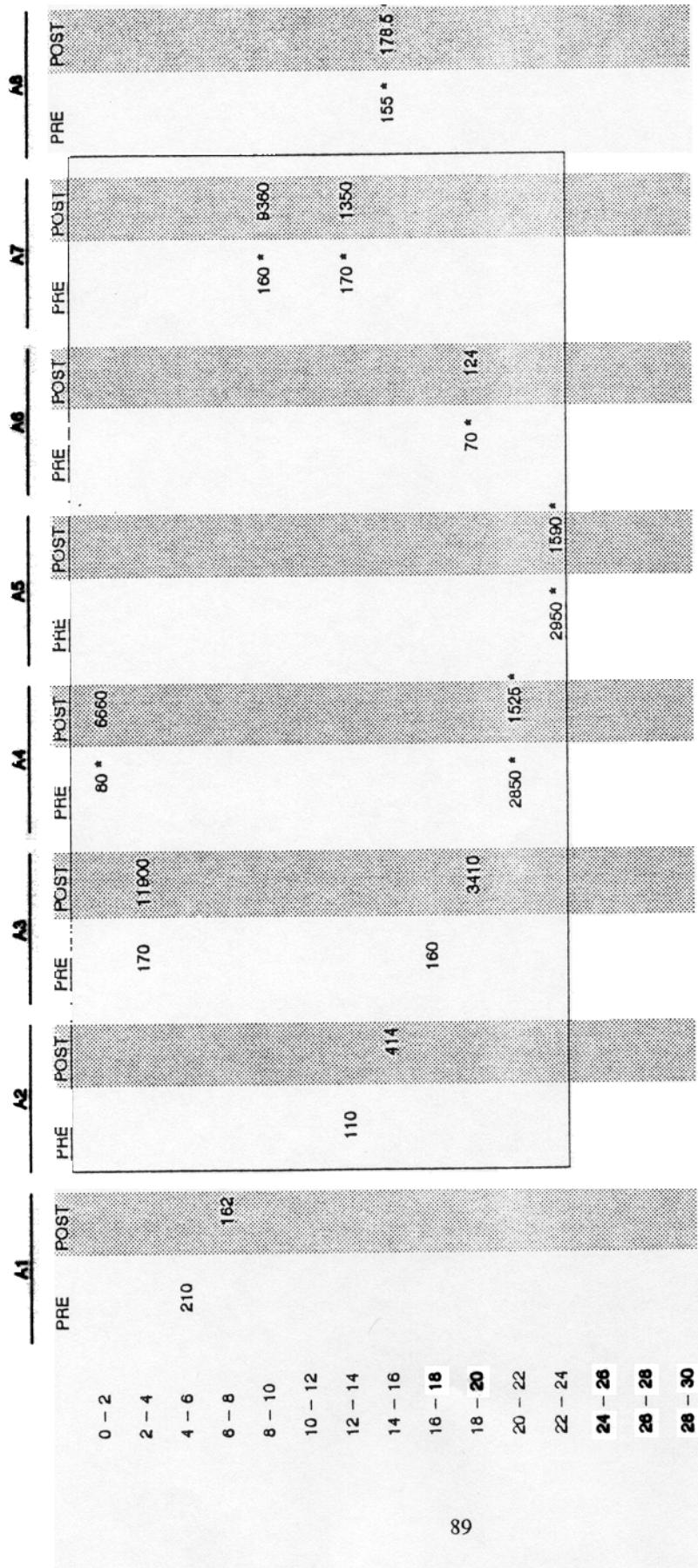


NA: Not analyzed

*: The value to the left of this symbol is the practical quantitation limit (PQL). The PQL is provided because the 4-methyl-2-pentanone concentration of this sample was below the PQL



Figure A-4. ITRI soil samples: initial and final 4-methyl-2-pentanone concentrations at depths of 24 feet or less, ppb (continued).



NA: Not analyzed
 *: The value to the left of this symbol is the practical quantitation limit (PQL). The PQL is provided because the acetone concentration of this sample was below the PQL.



Figure A-5. IITRI soil samples: initial and final acetone concentrations at depths of 24 feet or less, ppb.

TW7		TW1		TW2		B1		B2		B3		B4	
PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST
0 - 2													
2 - 4													
4 - 6	230 *	99.6	400										
6 - 8				4300									
8 - 10													
10 - 12													
12 - 14													
14 - 16	150 *	399.5 *	240	196									
16 - 18													
18 - 20													
20 - 22													
22 - 24													
24 - 26													
26 - 28													
28 - 30													

NA: Not analyzed
* The value to the left of this symbol is the practical quantitation limit (PQL). The PQL is provided because the acetone concentration of this sample was below the PQL.

Revised Zone
Heated Zone

Figure A-5. IITRI soil samples: initial and final acetone concentrations at depths of 24 feet or less, ppb (continued).

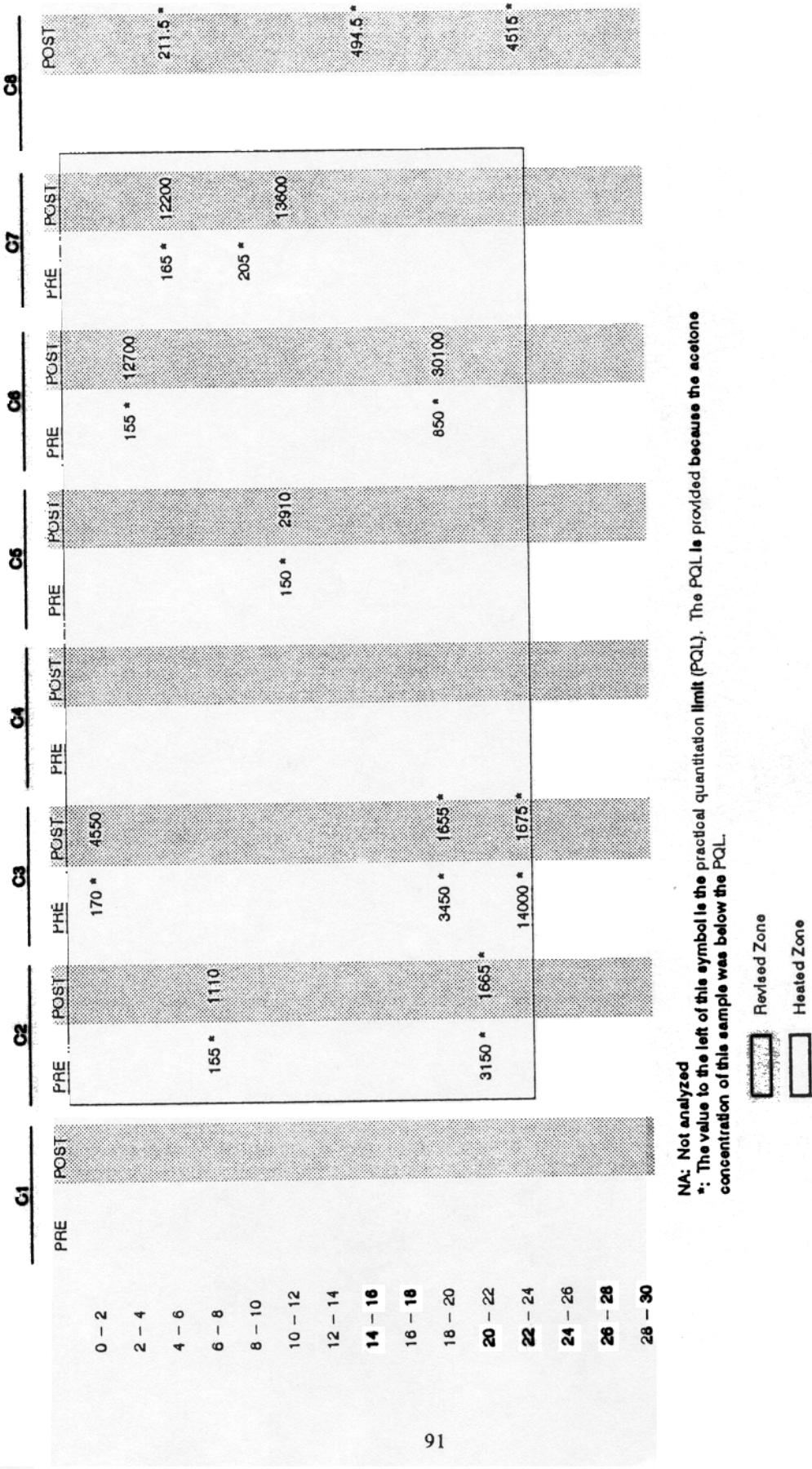


Figure A-5. IITRI soil samples: initial and final acetone concentrations at depths of 24 feet or less, ppb (continued).

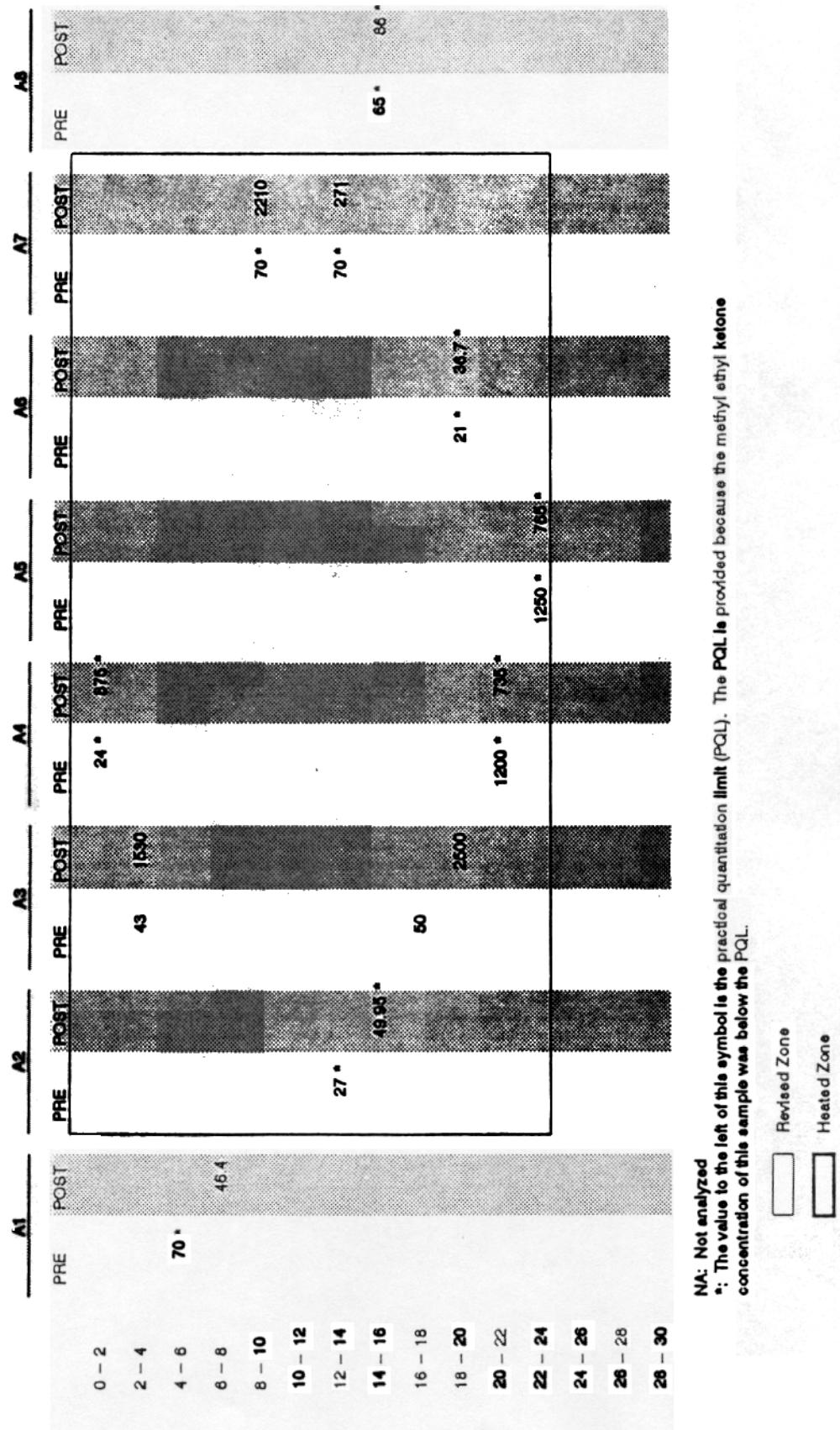


Figure A-6. IITRI soil samples: initial and final methyl ethyl ketone concentrations at depths of 24 feet or less, ppb.

TW7		TW1		TW2		B1		B2		B3		B4	
PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST
0 - 2													
2 - 4													
4 - 6	95 *	41.85 *	110										
6 - 8				110	2710								
8 - 10													
10 - 12													
12 - 14													
14 - 16	65 *	192 *	76 *	45.55 *	75 *	113							
16 - 18							710 *						
18 - 20													
20 - 22													
22 - 24													
24 - 26													
26 - 28													
28 - 30													

NA: Not analyzed
 *: The value to the left of this symbol is the practical quantitation limit (PQL). The PQL is provided because the methyl ethyl ketone concentration of this sample was below the PQL.

 Revised Zone

 Heated Zone

Figure A-6. IITRI soil samples: initial and final methyl ethyl ketone concentrations at depths of 24 feet or less, ppb (continued).

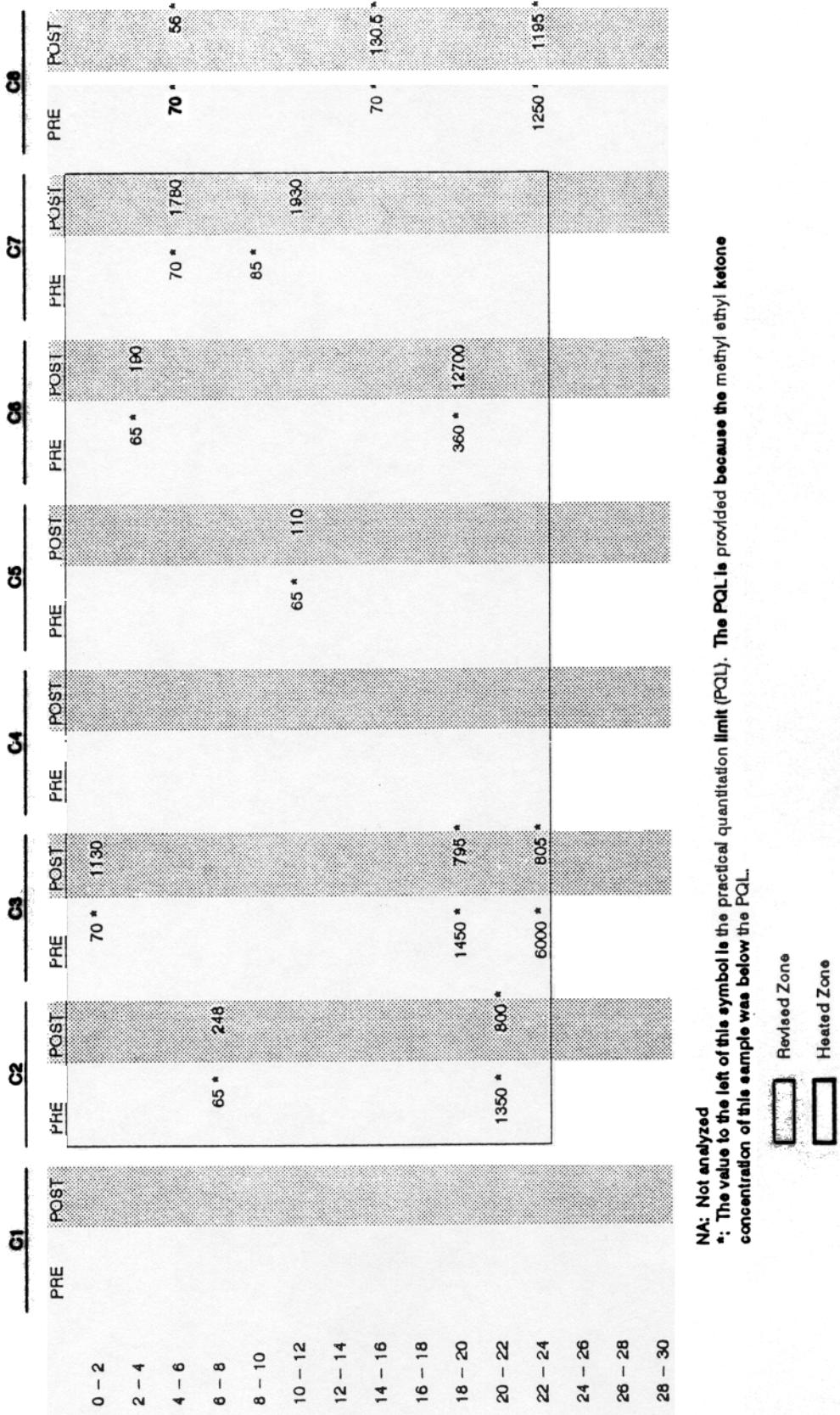


Figure A-6. IITRI soil samples: initial and final methyl ethyl ketone concentrations at depths of 24 feet or less, ppb (continued).

		A1		A2		A3		A4		A5		A6		A7		A8	
		PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST
0 - 2																	
2 - 4																	
4 - 6	69.5 *																
6 - 8		80.5 *															
8 - 10																	
10 - 12																	
12 - 14																	
14 - 16																	
16 - 18																	
18 - 20																	
20 - 22																	
22 - 24																	
24 - 26																	
26 - 28																	
28 - 30																	

NA: Not analyzed
 *: The value to the left of this symbol is the practical quantitation limit (PQL). The PQL is provided because the pyrene concentration of this sample was below the PQL.

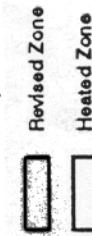


Figure A-7. IITRI soil samples: initial and final pyrene concentrations at depths of 24 feet or less, ppb.

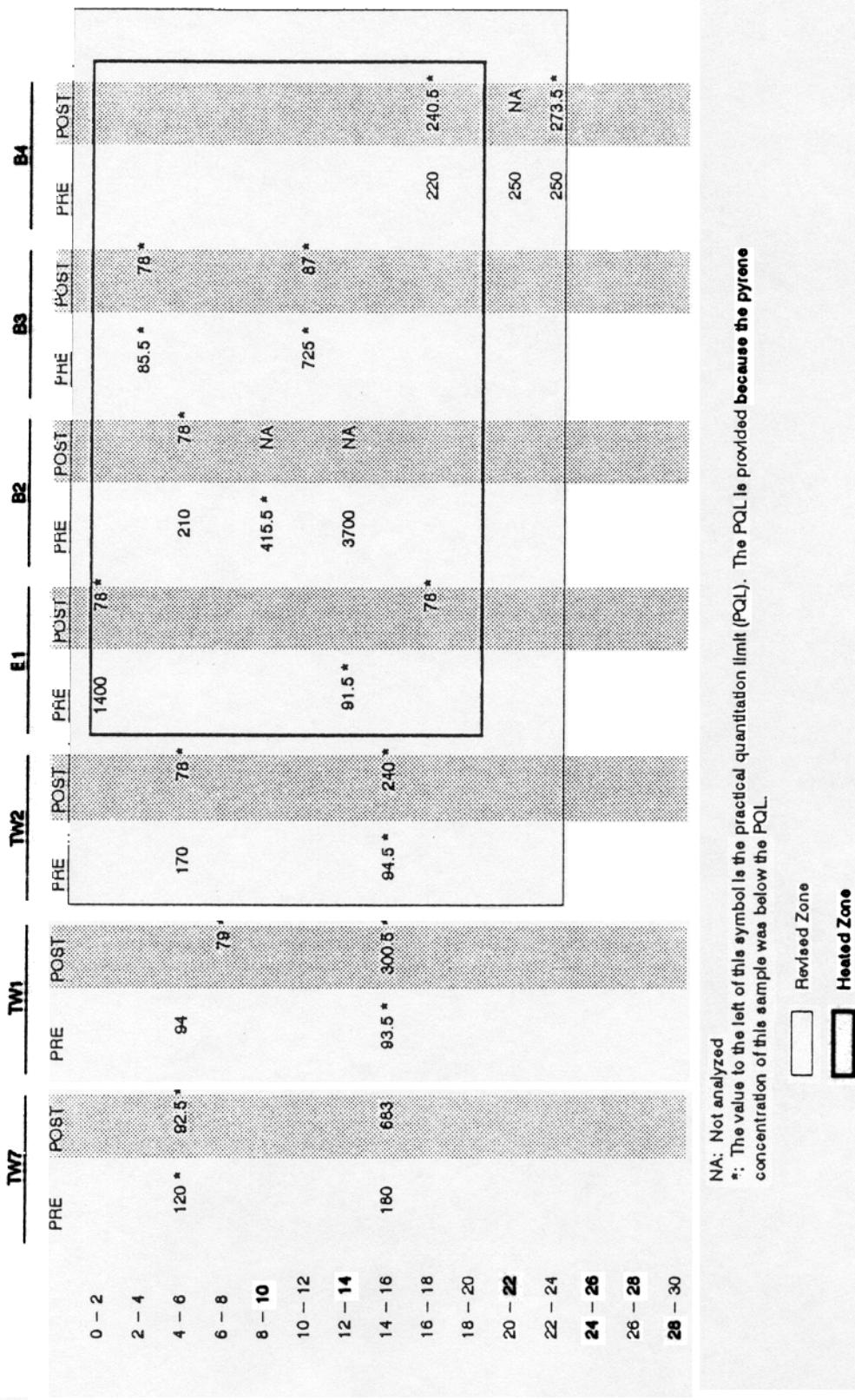


Figure A-7. IITRI soil samples: initial and final pyrene concentrations at depths of 24 feet or less, ppb (continued).

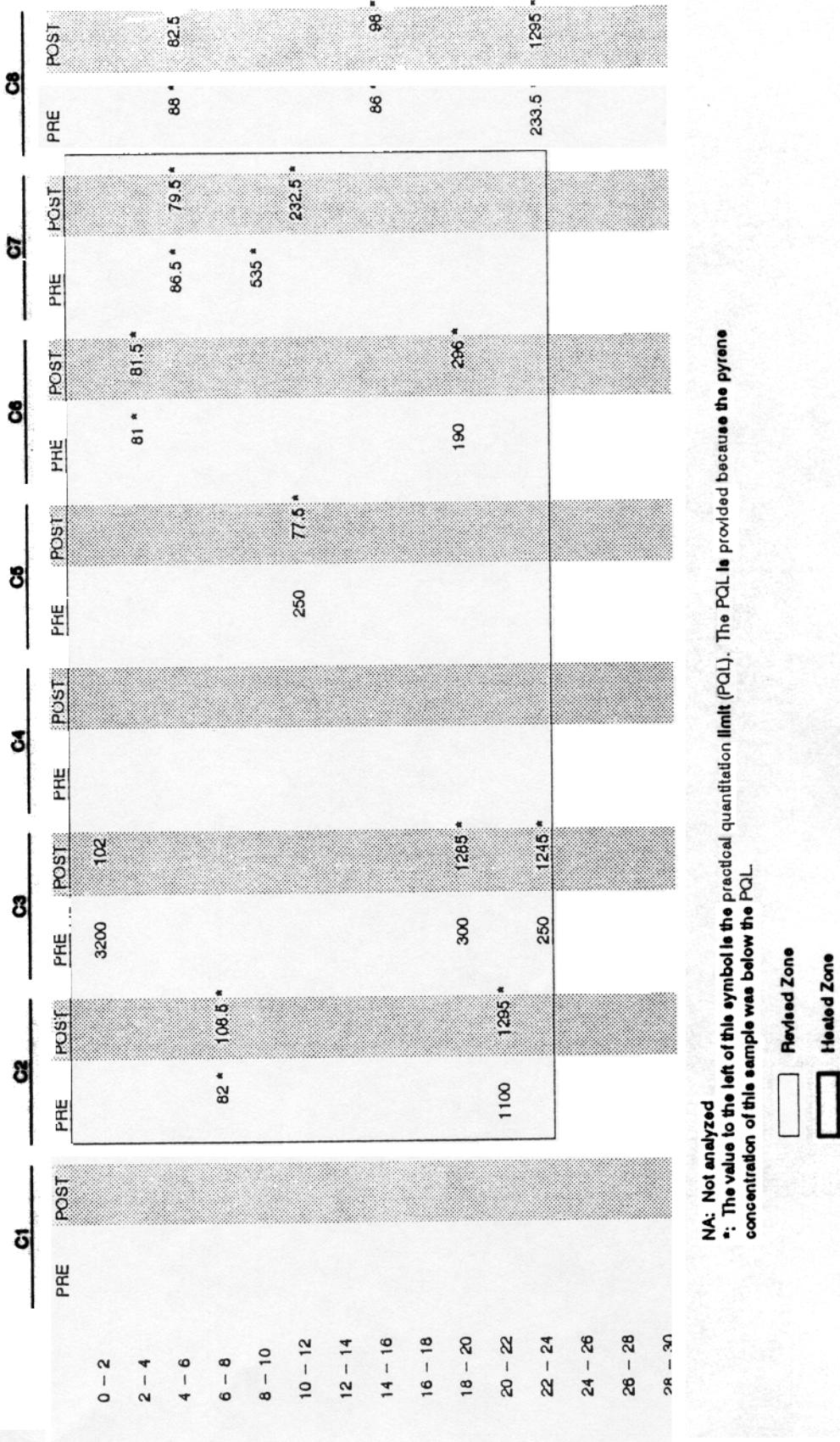


Figure A-7. IITRI soil samples: initial and final pyrene concentrations at depths of 24 feet or less, ppb (continued).

		<u>A1</u>	<u>A2</u>	<u>A3</u>	<u>A4</u>	<u>A5</u>	<u>A6</u>	<u>A7</u>	<u>A8</u>
		PRE	POST	PRE	POST	PRE	POST	PRE	POST
0 - 2						120	377*		
2 - 4				1000	305.5*				
4 - 6	520							119.5 *	306 *
6 - 8		504						125 *	314 *
8 - 10									
10 - 12									
12 - 14				129.5 *					
14 - 16				434 *					
16 - 18				17000					
18 - 20				12800					
20 - 22				5900					
22 - 24				7520					
24 - 26									
26 - 28									
28 - 30									

NA: Not analyzed

*: The value to the left of this symbol is the practical quantitation limit (PQL). The PQL is provided because the bis(2-ethylhexyl)phthalate concentration of this sample was below the PQL

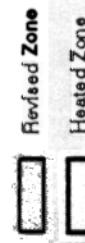


Figure A-8. IITRI soil samples: initial and final bis(2-ethylhexyl)phthalate concentrations at depths of 24 feet or less, ppb.

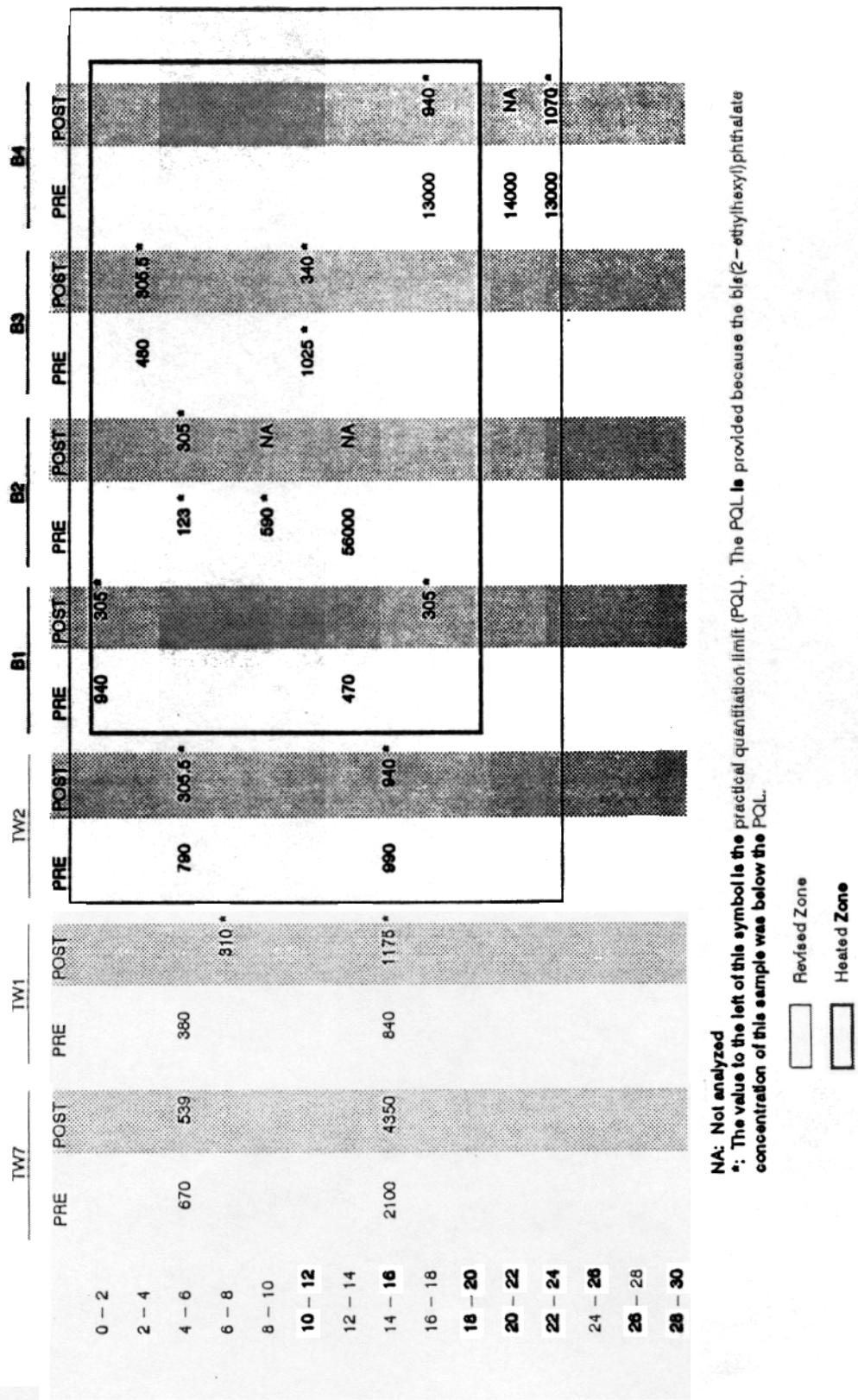


Figure A-8. IITRI soil samples: initial and final bis(2-ethylhexyl)phthalate concentrations at depths of 24 feet or less, ppb (continued).

C1		C2		C3		C4		C5		C6		C7		C8	
PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST
0 - 2				127 *	364.5 *					260	318.5 *				
2 - 4						2 - 4						122.5 *	311.5 *		
4 - 6															323 *
6 - 8				340	460										
8 - 10												760 *			
10 - 12															382 *
12 - 14															
14 - 16															
16 - 18															
18 - 20								14000	20600						
20 - 22								19000	6020						
22 - 24										9100	7290				
24 - 26															
26 - 28															
28 - 30															

NA: Not analyzed

*: The value to the left of this symbol is the practical quantitation limit (PQL). The PQL is provided because the bis(2-ethylhexyl)phthalate concentration of this sample was below the PQL.

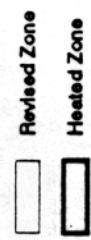


Figure A-8. IITRI soil samples: initial and final bis(2-ethylhexyl)phthalate concentrations at depths of 24 feet or less, ppb (continued).

In Figures A-1 through A-8, all contaminant concentrations are presented on a dry-weight basis. When a contaminant was not detected at or above its PQL, the PQL is presented. An asterisk to the right of a value indicates that value is the PQL, rather than a measured concentration.

The final statistical evaluation examined pre- and post-treatment analytical results from four zones: the revised design treatment zone, the heated zone, outside the revised design treatment zone, and outside the heated zone. Results for each of the four zones are presented in Tables A-3 through A-6. For all contaminants that exhibited statistically significant changes at confidence levels of 90 percent or greater, these tables present the specific confidence level and the estimated change in mean concentration. Tables A-3 and A-4 also present the 90 percent confidence interval (CI) for each contaminant.

A.1.3.2 Groundwater

One groundwater sample was collected by a USAF contractor, but it is not known where or how this sample was collected. The sample was also analyzed by a USAF contractor. These analyses were not part of the SITE demonstration and the quality of the data is unknown. No SVOC concentrations above detection limits were reported. VOC concentrations reported above detection limits are presented in Table A-7. These results are reported because they are the only available measurement of contaminant concentrations in the groundwater during the demonstration.

Post-treatment ketone concentrations in the soil were significantly higher than pretreatment concentrations, and the groundwater was proposed as a possible source of ketones. Approximately 6 months after post-treatment soil sampling, the SITE Program collected groundwater samples from three wells whose locations are shown in Figure 5 (MW10, MW09, and DW02). The results of these samples are presented in Table A-8. Ketones were detected at low concentrations in one of the three samples.

A.1.3.3 SVE Vapor Stream

Concentrations of TRPH and specific VOCs and SVOCs in the SVE vapor stream were monitored by a USAF contractor and were not part of the SITE demonstration. The results appear to indicate qualitatively removals of TRPH and certain VOCs and SVOCs but no conclusions can be drawn since the appropriateness of the methods used and the quality of the data are unknown.

Table A-3. Summary of Results Inside the Revised Design Treatment Zone

contaminant	Estimated Change in Mean Concentration	Confidence Level	Upper Bound of 90% CI	Lower Bound of 90% CI
TRPH	-60%	>95%	-21%	-79 %
Chlorobenzene	No statistically significant change at a confidence level of 90% or greater.			
2-hexanone	+457%	>99.9%	+750%	+264%
4-methyl-2-pentanone	+263%	>99%	+617%	+83%
Acetone	+1,073%	>99.9%	+2,245 %	+486%
Methyl ethyl ketone	+683 %	>99.9%	+1,477%	+288%
Pyrene	-87 %	>99.5%	68 %	-95 %
Bis(2-ethylhexyl)phthalate	48%	>97.5%	-23 %	-65%

Table A-4. Summary of Results Inside the Heated Zone

contaminant	Estimated Change in Mean Concentration	Confidence Level	Upper Bound of 90% CI	Lower Bound of 90% CI
TRPH	-95 %	>97.5 %	-77%	-99 %
Chlorobenzene	No statistically significant change at a confidence level of 90% or greater.			
2-hexanone	Final statistical evaluation was not conducted for this contaminant because it had no complete matched pairs of data.			
4-methyl-2-pentanone	Final statistical evaluation was not conducted for this contaminant because it had no complete matched pairs of data.			
Acetone	No statistically significant change at a confidence level of 90% or greater.			
Methyl ethyl ketone	No statistically significant change at a confidence level of 90% or greater.			
Pyrene	No statistically significant change at a confidence level of 90% or greater.			
Bis(2ethylhexyl)phthalate	No statistically significant change at a confidence level of 90% or greater.			

Table A-5. Summary of Results Outside the Revised Design Treatment Zone

Contaminant	Estimated Change in Mean Concentration	Confidence Level
TRPH	+88%	>95%
Chlorobenzene	No statistically significant change at a confidence level of 90% or greater.	
2-hexanone	Final statistical evaluation was not conducted for this contaminant because it had only one complete matched pair of data.	
4-methyl-2-pentanone	Final statistical evaluation was not conducted for this contaminant because it had only one complete matched pair of data.	
Acetone	No statistically significant change at a confidence level of 90% or greater.	
Methyl ethyl ketone	Final statistical evaluation was not conducted for this contaminant because it had only one complete matched pair of data.	
Pyrene	No statistically significant change at a confidence level of 90% or greater.	
Bis(2-ethylhexyl)phthalate	No statistically significant change at a confidence level of 90% or greater.	

Table A-6. Summary of Results Outside the Heated Zone

Contaminant	Estimated Change in Mean Concentration	Confidence Level
TRPH	No statistically significant change at a confidence level of 90% or greater.	
Chlorobenzene	No statistically significant change at a confidence level of 90% or greater.	
2-hexanone	+423%	>99.9%
4-methyl-2-pentanone	+249%	>99.5%
Acetone	+ 1347 %	>99.9%
Methyl ethyl ketone	+1049%	>99.9%
Pyrene	No statistically significant change at a confidence level of 90% or greater.	
Bis(2-ethylhexyl)phthalate	-37 %	>90%

Table A-7. Results of Groundwater Analysis for VOCs (Not Conducted by SITE Program)

Compound	Detection Limit, $\mu\text{g/L}$	Concentration, $\mu\text{g/L}$
	5	1,319
Toluene	5	195
Ethylbenzene	5	41
Xylene I	5	15
Xylene II	5	48
Chlorobenzene	5	5,747
1,2-dichlorobenzene	5	2,700
1,3-dichlorobenzene	5	230
1,4-dichlorobenzene	5	964

Table A-8. Results of Groundwater Analyses Conducted by the SITE Program

Well ID Number	Measurement	Result
MW10	TRPH (mg/L)	4.92
	Volatiles ($\mu\text{g/L}$)	
	Acetone	61.9
	Benzene	782
	Chlorobenzene	25,500
	Trans- 1,2-dichloroethene	14
	Methyl ethyl ketone	16.4
	4-Methyl-2-pentanone	11.5
	Toluene	51.2
	Vinyl Chloride	28
	Semivolatiles ($\mu\text{g/L}$)	
	2-Chlorophenol	193
	1,2-Dichlorobenzene	11,200
	1,3-Dichlorobenzene	760
	1,4-Dichlorobenzene	2160
	2,4-Dichlorophenol	36.3
	2-Methylnaphthalene	16.2
	Naphthalene	121
	Phenol	22.3
	1,2,4-Trichlorobenzene	51.4

Table A-8. Results of Groundwater Analyses Conducted by the SITE Program (Continued)

Well ID Number	Measurement	Result
MW09	TRPH (mg/L)	0.83
	Volatiles ($\mu\text{g/L}$)	
	Benzene	596
	Chlorobenzene	12,000
	Ethylbenzene	91.9
	Toluene	5.65
	Vinyl Chloride	10.2
	Xylenes	12
	Semivolatiles ($\mu\text{g/L}$)	
	2-Chlorophenol	37.4
	1,2-Dichlorobenzene	163
	1,3-Dichlorobenzene	23.5
	1,4-Dichlorobenzene	183
	2-Methylnaphthalene	59.2
	Naphthalene	71.1
	Phenol	3.58
DW02	TRPH (mg/L)	267
	Volatiles ($\mu\text{g/L}$)	
	Chlorobenzene	15,700
	Semivolatiles ($\mu\text{g/L}$)	
	Acenaphthene	7.79
	2-Chlorophenol	22.1
	1,2-Dichlorobenzene	1820
	1,3-Dichlorobenzene	152
	1,4-Dichlorobenzene	529
	bis(2-ethylhexyl)phthalate	218
	Fluoranthene	29.3
	Fluorene	7.51
	2-Methylnaphthalene	124
	Naphthalene	86.8
	Phenanthrene	7.17
	1,2,4-Trichlorobenzene	15.5

Graphs of the vapor stream data are provided for selected contaminants. In each of the graphs, the vapor stream contaminant concentration is shown as a function of time. The time is given as "Day of Treatment," where Day 1 is defined as the first day that a vapor stream sample was collected. It is important to note the application of RF energy to the soil did not begin until Day 5 and was discontinued on Day 66.

Figure A-9 illustrates vapor stream concentrations of total petroleum hydrocarbons (JTH). Due to the non-specific nature of the TRPH method used to analyze soil samples during the demonstration, it is not possible to correlate soil TRPH results with vapor stream TPH results. Figures A-10 through A-17 illustrate vapor stream concentrations for the following VOCs: benzene; toluene; ethylbenzene; chlorobenzene; xylenes; 2-hexanone; 2-butanone (synonym for methyl ethyl ketone); and acetone. This list includes all of the VOCs included in the original or final statistical evaluations, except 4-methyl-2-pentanone, which was not detected in any of the vapor stream samples. Graphs of SVOC vapor stream concentrations are not provided because, with two exceptions, no SVOCs were detected in the vapor stream. The two exceptions are 1,2-dichlorobenzene and 1,4-dichlorobenzene, which were each detected at 1.5 milligrams per cubic meter on March 31, 1993 (before the RFH system was turned on) and were not detected in any subsequent samples.

Several trends can be observed in the vapor stream data. Many of the contaminants that were present in the pretreatment soil samples (TPH, benzene, toluene, ethylbenzene, chlorobenzene, and xylenes) were detected in the vapor stream shortly after the SVE system was turned on. It does not appear that RFH contributed significantly to these early spikes, since the RF power was not turned on until Day 5 and since soil heats slowly. After these early spikes, most contaminants were not detected in significant concentrations until Day 44 or later. These later spikes may be due to contaminants that were volatilized by the RFH, then collected by the SVE system. Alternatively, they may be due to a pocket of contamination that had a long travel time before being collected by the SVE system.

It can also be observed that, in general, significant concentrations of ketone were not detected in the vapor stream until Day 44 or later. This could be used to support either of the theories that were presented in Section 4 to explain the increases in ketone concentrations in the revised design treatment zone.

A. 1.3.4 Condensate

Condensate from the vapor treatment system was collected in a 55-gallon (0.21-cubic-meter) drum. When the drum became full or nearly full, its contents were pumped to a 20,000-gallon (76-cubic-meter) tank used to store water from dewatering activities. The combined water was subsequently transferred to a Kelly AFB facility for treatment. The total quantity of condensate was not measured, but the date, time, and approximate quantity were recorded in a field log each time the condensate drum was emptied. Based on this information, it is estimated that 800 gallons (3 cubic meters) of condensate were collected.

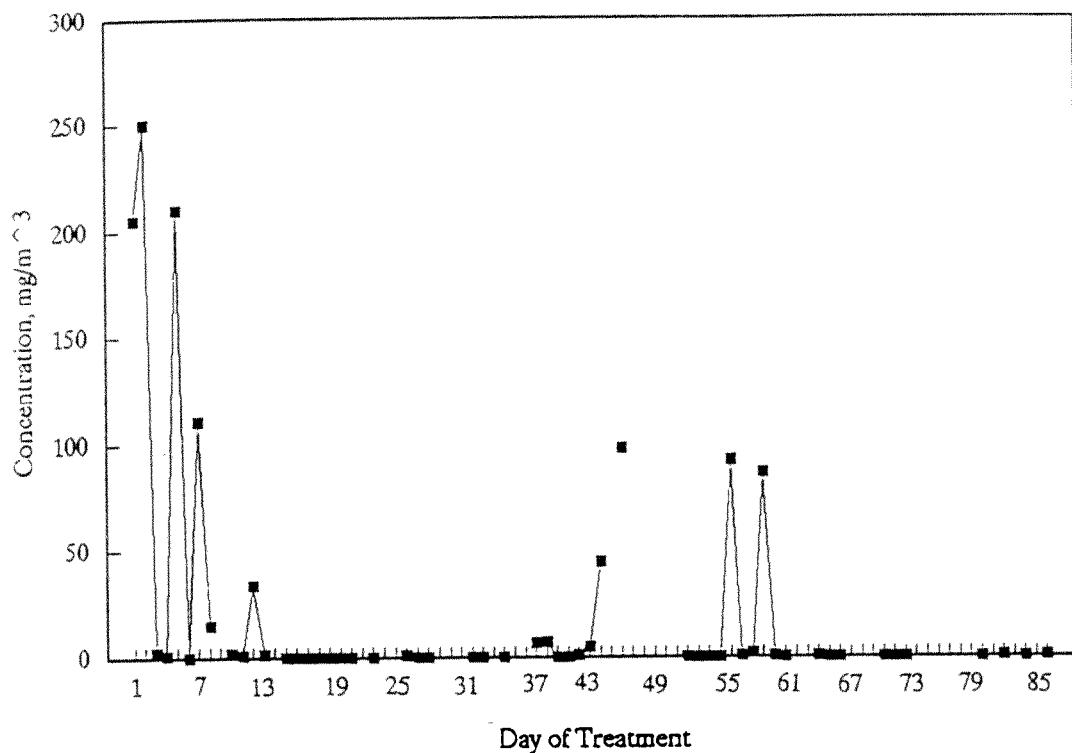


Figure A-9. TPH SVE vapor stream concentrations

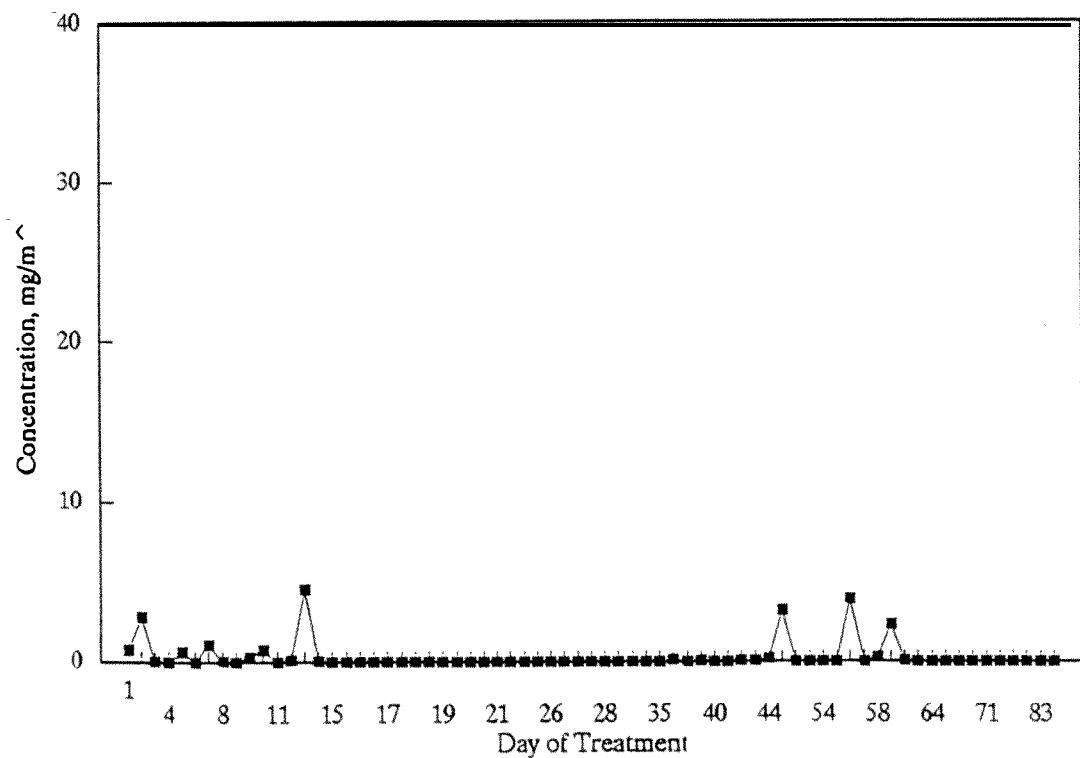


Figure A-10. Benzene SVE vapor stream concentrations.

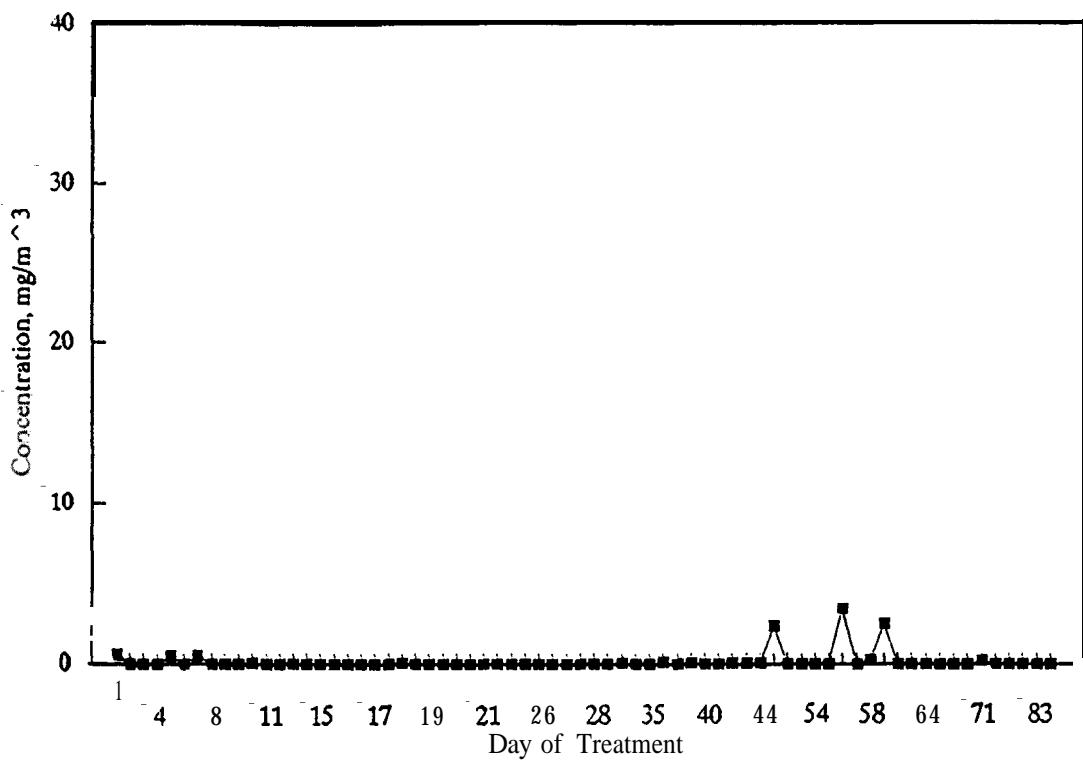


Figure A-11. Toluene SVE vapor stream concentrations.

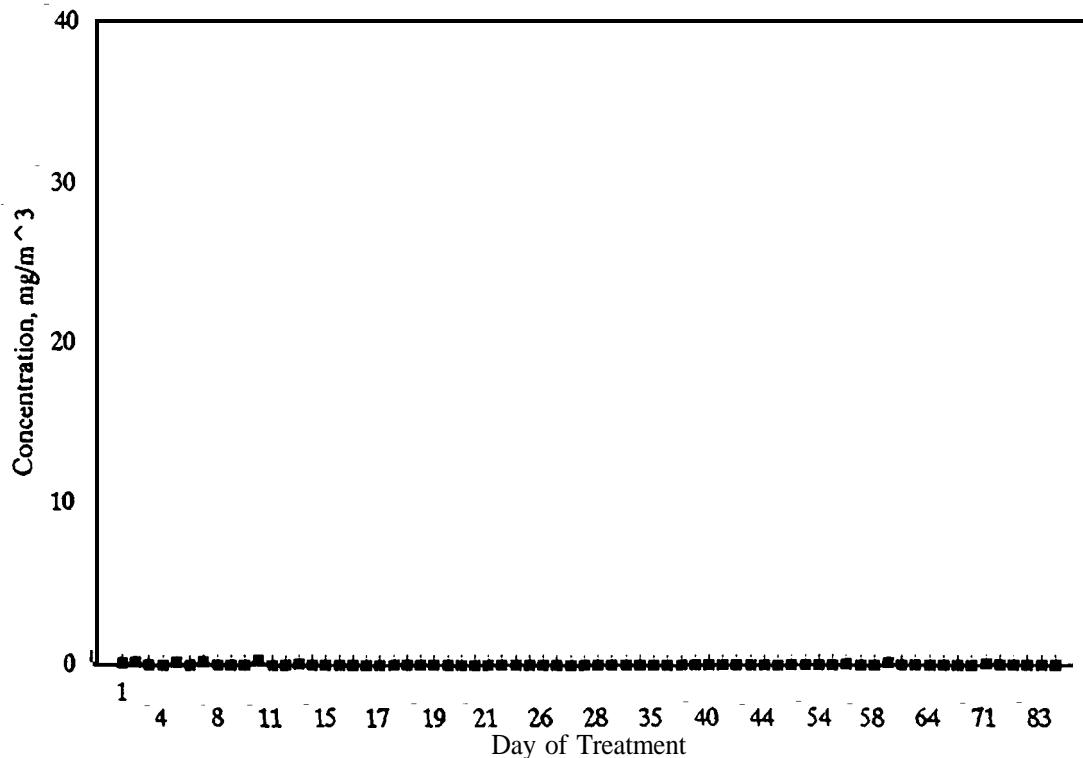


Figure A-12. Ethylbenzene SVE vapor stream concentrations.

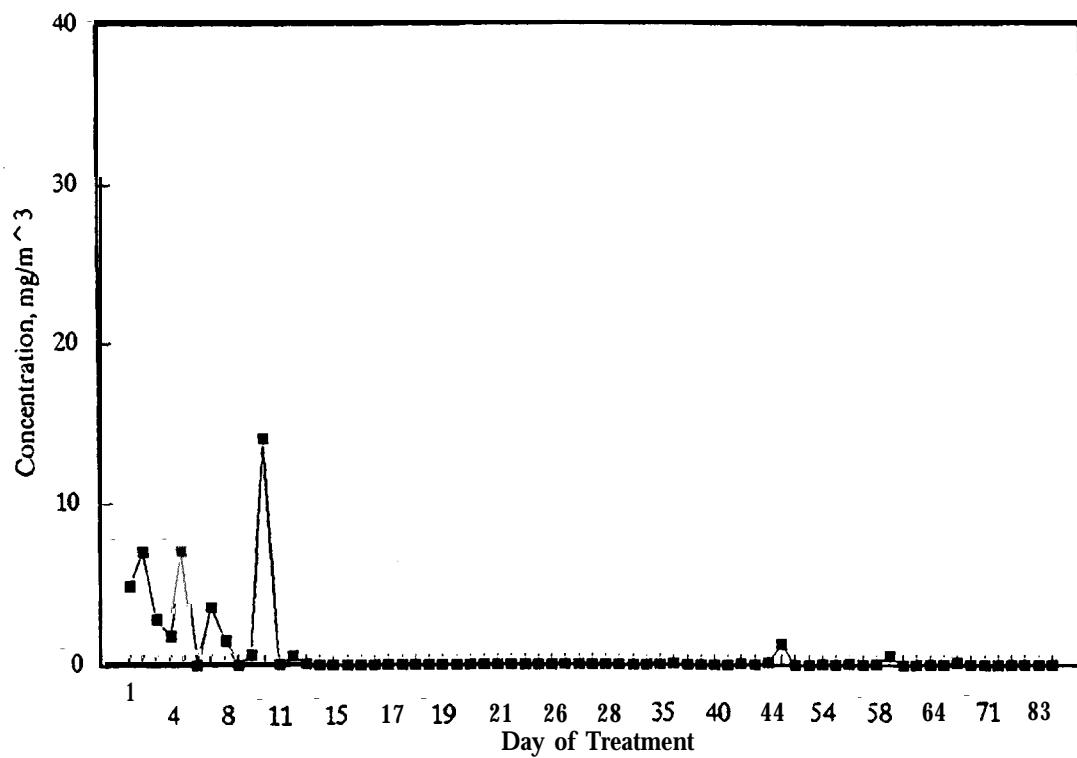


Figure A-13. Chlorobenzene SVE vapor stream concentrations.

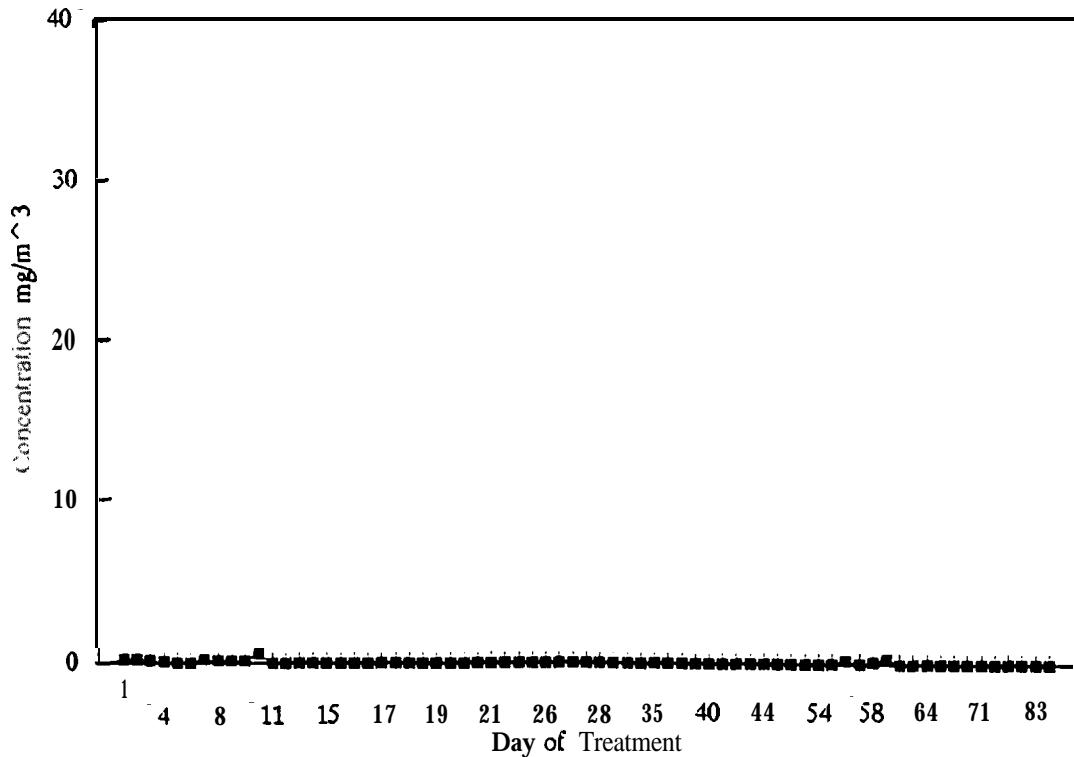


Figure A-14. Total xylene SVE vapor stream concentrations.

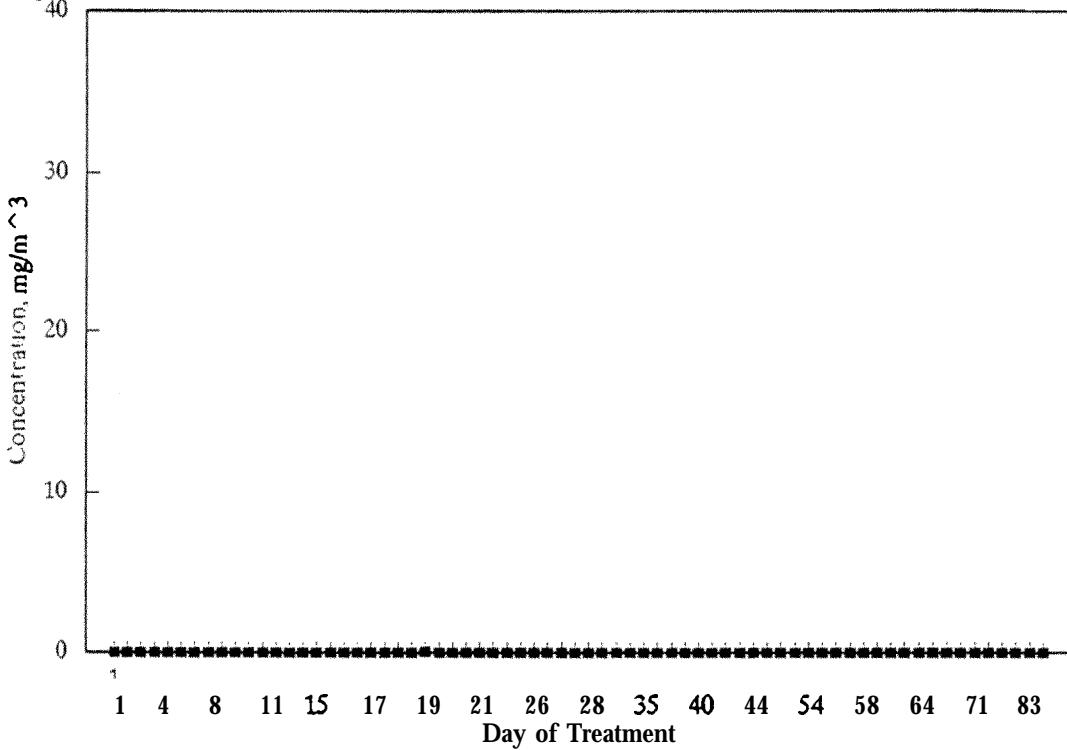


Figure A-15. 2-Hexanone SVE vapor stream concentrations.

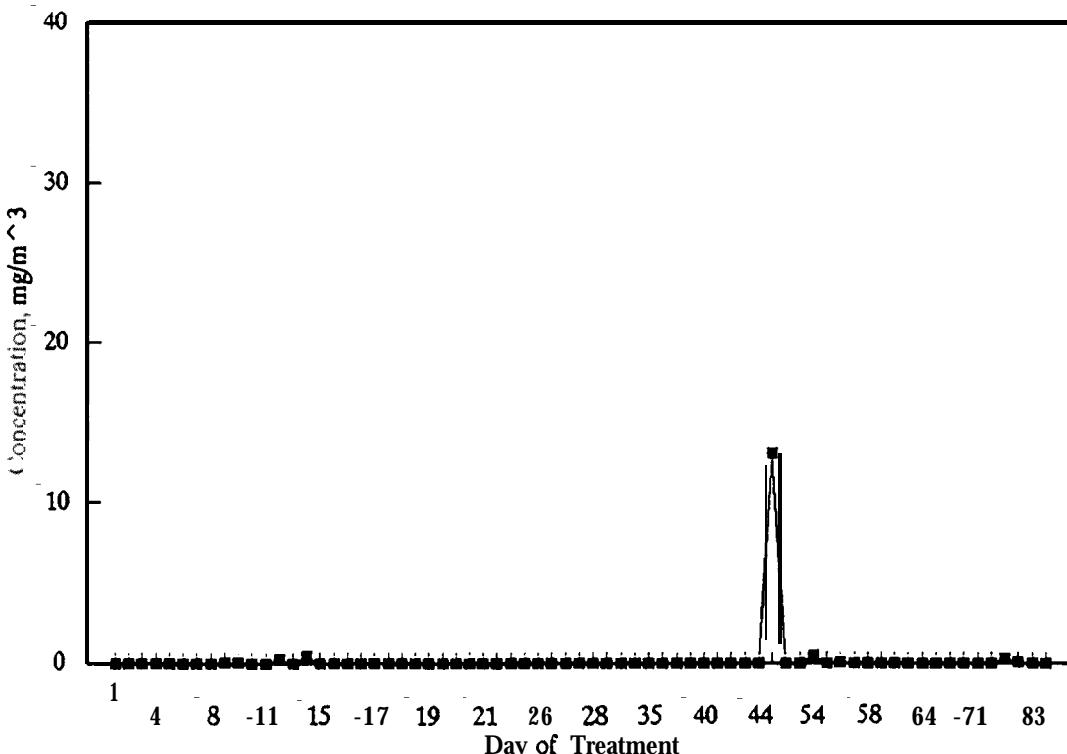


Figure A-16. 2-Butanone (MEK) SVE vapor stream concentrations.

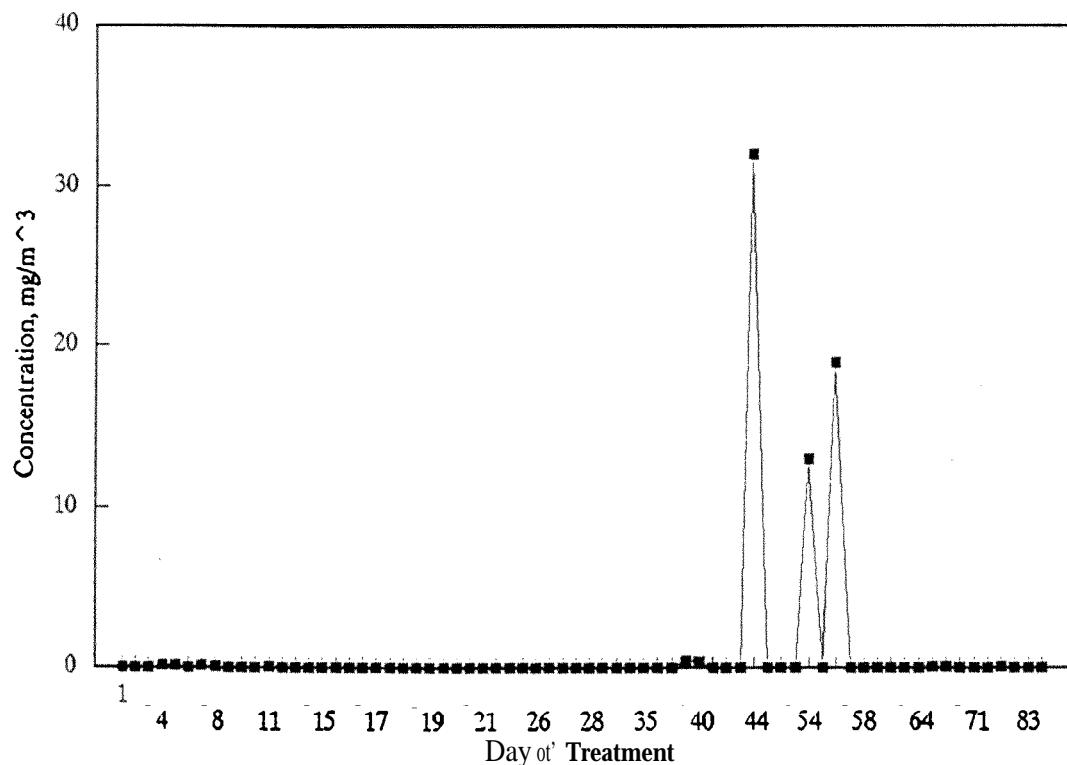


Figure A-17. Acetone SVE vapor stream concentrations.

Two condensate samples were collected by a USAF contractor on May 14, 1993. The condensate samples were analyzed by a USAF contractor. These analyses were not part of the SITE demonstration and the quality of the data is unknown. The laboratory report indicates that SVOC concentrations were determined using Methods 3510 and 8270 from SW-846 [2]; VOC concentrations were determined using Methods 5030 and 8260 from SW-846 [2]; and TPH was determined using EPA Method 418.1 [3]. Concentrations reported above detection limits are presented in Tables A-9, A-10, and A-11.

A.1.3.5 Moisture

Moisture analyses were conducted so that soil sample concentration results could be converted to dry weight results. Figure A-18 presents the results of moisture analyses in the same format (described in Subsection A.1.3.1) used to present the results of the chemical analyses. Based on the final statistical evaluation, there were statistically significant decreases in percent moisture inside the revised design treatment zone, inside the heated zone, outside the revised design treatment zone, and outside the heated zone. Moisture results for all zones are summarized in Table A-12.

Table A-9. Results of Condensate Analysis for SVOCs (Not Conducted by SITE Program)

Contaminant	Detection Limit, $\mu\text{g}/\text{L}$	Sample Concentration, $\mu\text{g}/\text{L}$
Benzoic acid	50	140
Benzyl alcohol	20	26
Bis(2-ethylhexyl)phthalate	10	95
Di-n-butylphthalate	10	16
2,4-Dimethylphenol	10	50
2-Methylphenol	10	14
4-Methylphenol	10	300
Phenol	10	120

Table A-10. Results of Condensate Analysis for TPH (Not Conducted by SITE Program)

Contaminant	Detection Limit, mg/L	Sample Concentration, mg/L
TPH	1	5

Table A-11. Results of Condensate Analysis for VOCs (Not Conducted by SITE Program)

Contaminant	Detection Limit, mg/L	Sample 1 Concentration, mg/L	Sample 2 Concentration, mg/L
Acetone	1	2.4	12
Bromomethane	0.1	<0.1	1.3
Benzene	0.05	<0.05	0.06
Chlorobenzene	0.05	0.07	0.09

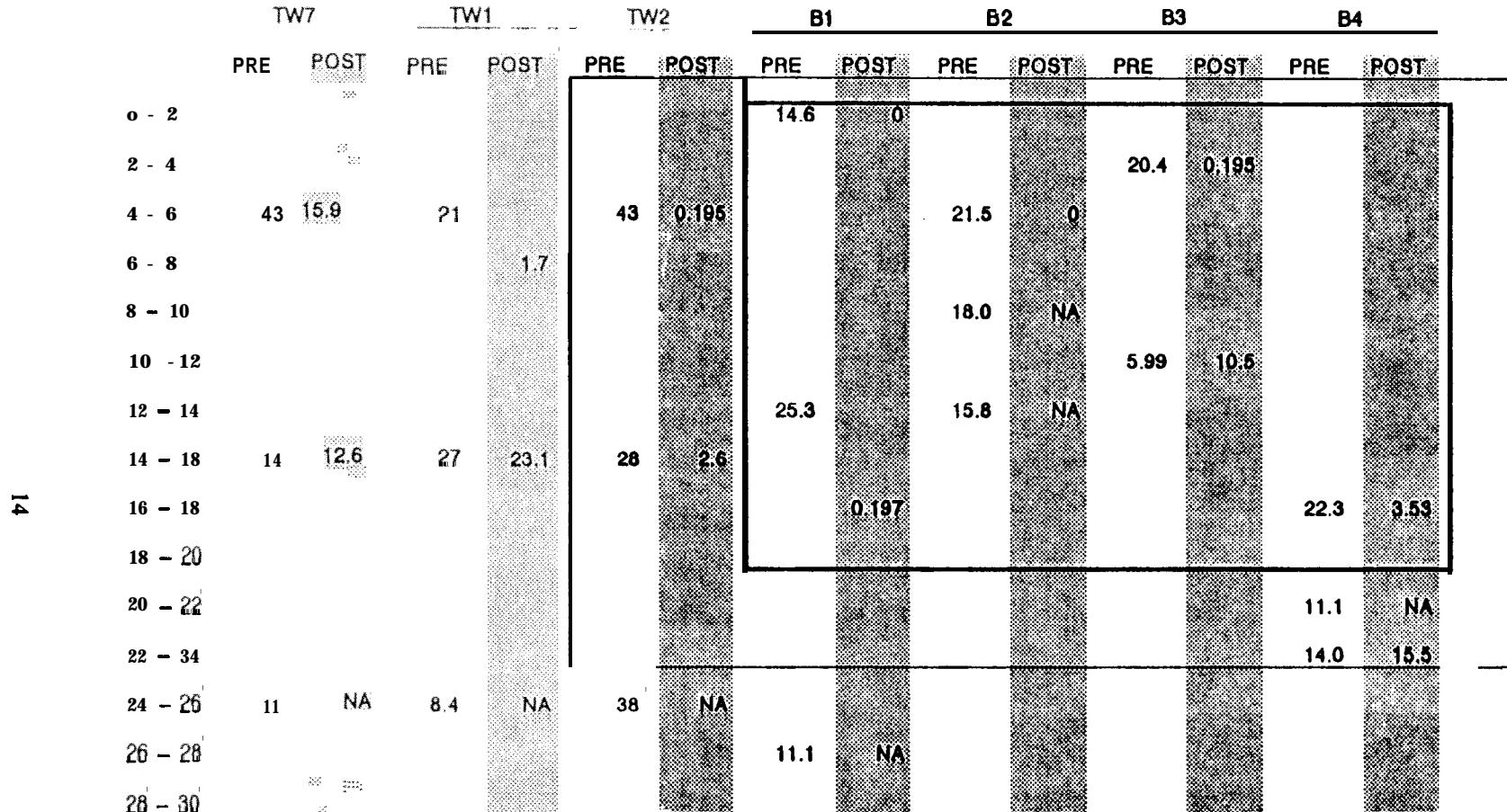
		A1		A2		A3		A4		A5		A6		A7		A8	
		PRE	POST														
0 - 2																	
2 - 4																	
4 - 6	24																
6 - 8	3.61																
8 - 10																	
10 - 12																	
12 - 14																	
14 - 16																	
16 - 18																	
18 - 20																	
20 - 22																	
22 - 24																	
24 - 26																	
26 - 28																	
28 - 30																	

NA: Not analyzed

 Revived Zone

 Heated Zone

Figure A-18. Moisture content analyses



NA: Not analyzed

 Revised Zone

 Heated Zone

Figure A-18 Moisture content analyses (continued)

	C1	c2	C3	C4	C5	C6	C7	C8				
	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST
15	0 - 2			24.1	16.6							
	2 - 4								16.0	4.32		
	4 - 6										21.1	2.38
	6 - 8		16.9	28.2								22.6
	8 - 10									36.2	0.559	
	10 - 12						14.0	0				
	12 - 14											20.7
	14 - 18											20.5
	16 - 18											
	18 - 20			25.0	10.9				24.0	21.3		
	20 - 22		17.3	11.7								
	22 - 24			8.53	11.6							12.9
	24 - 26								16.5	NA		
	26 - 28											
	28 - 30						16.8	NA				

VA: Not analyzed

 Revised Zone

 Heated Zone

Figure A-18. Moisture content analyses (continued).

Table A-12. Summary of Percent Moisture Results

	Estimated Change in Mean Concentration	Confidence Level
Inside Revised Design Treatment Zone	-86 %	>99.9%
Inside Heated Zone	-97 %	>97.5%
Outside Revised Design Treatment Zone	-53 %	>95%
Outside Heated Zone	-73 %	>99.9%

A.2 PHYSICAL ANALYSES

A.2.1 Particle Size Distribution

Particle size distribution analyses were conducted to characterize the soil. For evaluation purposes, particle size distribution data are simplified into three categories: gravel, sand, and fines. Particles that are less than 3 inches (0.08 meters) in diameter but will not pass through a #4 sieve (4.750 millimeters) are classified as gravel, particles that will pass through a #4 sieve (4.750 millimeters) but will not pass through a #200 sieve (0.075 millimeters) are classified as sand, and particles that will pass through a #200 sieve (0.075 millimeters) are classified as fines.

Pretreatment particle size distribution analyses were conducted using two procedures, which will be referred to as dry-sieving and wet-sieving. The dry-sieving results should accurately represent the fraction of gravel present at the site, but probably do not accurately represent the fractions of sand and fines. The actual fraction of sand is likely to be lower than the dry-sieving results indicate, and the fraction of fines correspondingly higher. Dry-sieving results should, therefore, only be used to characterize the site in terms of the fraction of gravel and the fraction of sand plus fines. Wet-sieving results should be used to characterize the site in terms of the individual fractions of sand and fines.

Tables A-13, A-14, and A-15 summarize results of particle size distribution analyses. In Table A-13, wet-sieving and dry-sieving results were averaged when both procedures were conducted for samples from a given sampling location.

The USAF contractor prepared a geologic profile of Site S-1 prior to the demonstration. The revised design treatment zone is located within Site S-1, near SB01. The geologic profile is presented in Figure A-19, and the legend associated with the geologic profile is presented in Figure A-20.

Table A-13. Results of Particle Size Distribution Analyses Using Wet- and Dry-Sieving – Pretreatment Samples

Sample Location (Borehole, Depth) ^d	Percent Gravel	Percent Sand and Fines
A1, 4'-6'	33.6	66.4
A2, 12'-14'	20.2	78.8
A3, 2'-4'	40.9^a	59.1^b
A3, 16'-18'	16.6	83.4
A4, 20'-22'	53.1 ^a	46.9
A5, 22'-24'	77.5	22.5
A6, 18'-20'	73.7	26.3
A7, 8'-10'	42.6	57.4
A7, 12'-14'	6.9	93.1
A8, 14'-16'	31.2 ^a	68.8
A8, 28'-30'	58.3	41.7
B1, 0'-2'	32.2 ^a	67.8
B1, W-14'	18.1	81.9
B1, 26'-28'	92.8	7.2
B2, 4'-6'	5.8	94.2
B2, 8'-10'	66.9	33.1
B2, 12'-14' ^c	4.1	95.9
B3, 2'-4'	38.5	61.5
B3, 10'-12'	45.4'	54.6
B4, 16'-18'	77.2	22.8
B4, 20'-22 ^c	37	63
B4, 22'-24'	86.2	13.8
C2, 6'-8'	13.9	86.1
C3, 0'-2'	28.7^a	71.3
C3, 18'-20'	0.3	99.7
C3, 22'-24 ^c	78.8	21.2
C5, 10'-12 ^c	40.5	59.5
C6, 2'-4'	26.3	73.7
C6, 18'-20'	63.7	36.3

Table A-13. Results of Particles Size Distribution Analyses Dug in Wet- and Dry-Sieving – Pretreatment Samples (Continued)

Sample Location (Borehole, Depth) ^d	Percent Gravel	Percent Sand and Fines
C6, 24'-26'	64.5	35.5
C7, 4'-6'	32.5	67.5
C7, 8'-10'	42.7	57.3
C8, 4'-6'	33.4	66.6
C8, 14'-16'	27.5	72.5
C8, 22'-24'	85.8	14.2
TW1, 4'-6' ^c	34	66
TW1, 14'-16'	14.3	85.7
TW2, 4'-6' ^c	29.3	70.7
TW2, 14'-16'	30.5^a	69.5
TW2, 24'-26'	92.3	7.7
TW7, 4'-6'	39.9	60.1
TW7, 14'-16'	42.3	57.7
TW7, 24'-26'	71.9	28.1
Average	43.1	56.9

a Average value of wet- and dry-sieving value taken from the sample location.

b Actual value is slightly higher. Determined by subtracting the % gravel value from 100%.

c Wet-sieving value.

d Sample intervals are given in feet because 2-foot-long split spoon was used for sampling To convert to meters, multiply by 0.3048

Table A-14. Results of Particle Size Distribution Analyses Using Wet-Sieving Only — Pretreatment Samples

Sample Location (Borehole, Depth)	Percent Gravel	Percent Sand	Percent Fines
A3, 2'-4'	33.6	27.9	38.5
A4, 20'-22'	73.8	17.1	9.1
A8, 14'-16'	26.3	25.0	48.7
B1, 0'-2'	48.0	30.0	22.0
B2, 12'-14'	4.1	17.8	78.1
B3, 10'-12'	49.7	26.0	24.3
B4, 20'-22'	37.0	28.0	35.0
C3, 0'-2'	30.3	20.7	49.0
C3, 22'-24'	78.8	14.7	6.5
C5, 10'-12'	40.5	34.0	25.5
TW1, 4'-6'	34.0	26.6	39.4
TW2, 4'-6'	29.3	30.1	40.6
TW2, 14'-16'	18.9	33.0	48.1
Average	38.8	25.5	35.8

Sample intervals are given in feet because a 2-foot-long split spoon was used for sampling. To convert to meters, multiply by 0.3048

Table A-15. Results of Particle Size Distribution Analyses Using Wet-Sieving Only – Post-Treatment Samples

Sample Location (Borehole, Depth) ^(a)	Percent Gravel	Percent Sand	Percent Fines
A4, 20'-22'	47.6	23.4	29.0
A7, 8'-10'	24.2	35.3	40.5
A8, 14'-16'	34.2	36.0	29.8
B2, 4'-6'	48.8	44.9	6.3
B3, 2'-4'	40.3	44.2	15.5
B3, 10'-12'	26.6	60.4	13.0
B4, 16'-18'	22.5	39.7	37.8
B4, 22'-24'	55.7	29.8	14.5
C2, 6'-8'	30.1	30.1	39.8
C3, 22'-24'	73.8	17.6	8.6
C8, 22'-24'	81.6	11.2	7.2
Average	44.1	33.9	22.0

a Sample intervals are given in feet because • a 2-foot-long split spoon was used for sampling. To convert to meters, multiply by 0.3048.

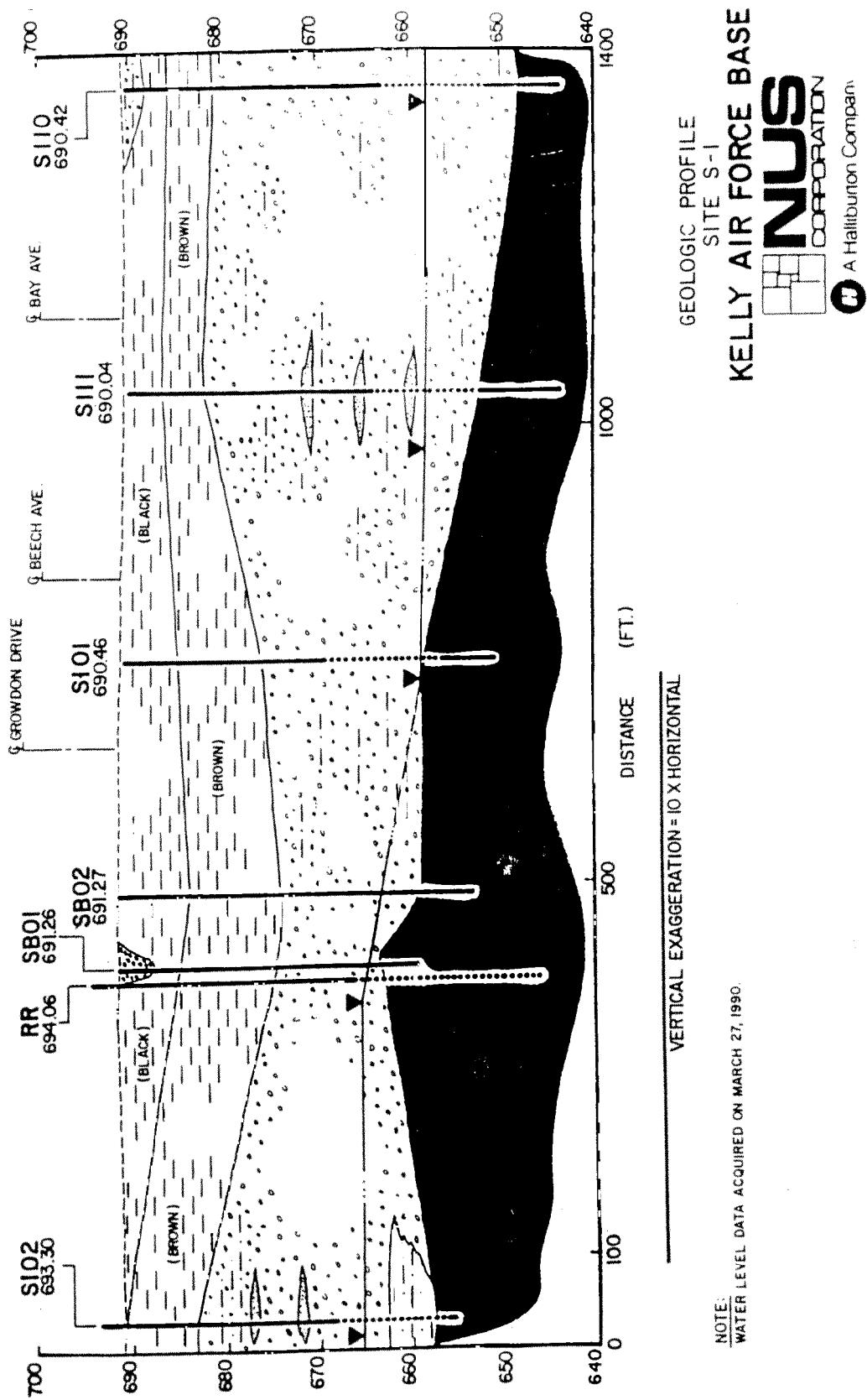
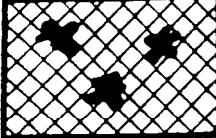
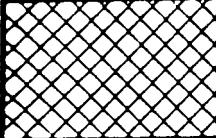
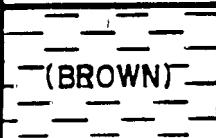
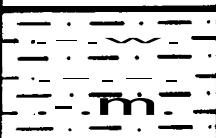
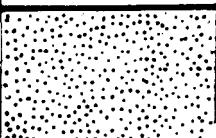
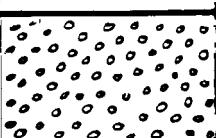


Figure A-19. Geologic profile of Site S-1 at Kelly AFB.

SYMBOL	LITHOFACIES OR MATERIAL TYPE	DESCRIPTION	
	LANDFILL MATERIAL	AQUIFER OVERBURDEN INFILTRATION COVER	HIGHLY VARIABLE FILL MATERIAL (CLAY-GRAVEL) CONTAINING GARBAGE, METAL, WOOD, PLASTIC, AND OTHER LANDFILL MATERIALS.
	FILL MATERIAL		HIGHLY VARIABLE: SILTY CLAY WITH VARYING GRAVEL CONTENT. SAND ALSO COMMON. CONCRETE AND ASPHALT ARE TYPICAL "NON-NATURAL" CONSTITUENTS. DIFFICULT TO DISTINGUISH FROM ALLUVIAL SEDIMENTS IN MANY CASES (SUCH AS LEN CREEK PUMP TEST LOCATION).
	CLAY (BLACK)		ORGANIC-RICH CLAY, TRACE SILT, FINE TO COARSE SAND SIZE CALCHE, STIFF, PLASTIC WHEN MOIST, NO VISIBLE INTERNAL LAYERING.
	CLAY (BROWN)		TYPICALLY LIGHT TO DARK ORANGE-TO RED-BROWN CLAY, TRACE AMOUNTS OF SILTANO SAND. ISOLATED GRAVEL CLASTS, CALCHE COMMON IN BROWN MY. TRANSITIONAL WITH OVERLYING BLACK CLAY (TYPICALLY AS NODULES). SOMETIMES APPEARS MOTTLED OR CRUDELY LAMINATED.
	SILT		BROWN TO LIGHT BROWN SILT, TRACE AMOUNTS OF CLAY, AND FINE SAND. ISOLATED GRAVEL, CALCHE COMMON IN UPPER PART OF UNIT. VERY THIN VUGS TYPICALLY FILLED WITH BLACK ORGANIC MATERIAL. IN SOME AREAS (UNION PACIFIC RR YARD) THIS UNIT IS CEMENTED WITH CALCHE.
	SAND		FINE TO COARSE SAND, TYPICALLY FINE- TO MEDIUM-GRAINED. <40% CLAY, YLT. AND GRAVEL TEXTURALLY IMMATURE, SORTING IS VARIABLE BUT USUALLY POOR.
	CLAYEY GRAVEL		TYPICALLY BROWN TO GRAY, POORLY SORTED LIMESTONE-CHERT GRAVEL WITH CLAY-SILT MATRIX >20% BUT <80%, OFTEN SANDY, LOOSELY CONSOLIDATED, THIN CALCHE COATINGS COMMON ON GRAVEL CLASTS. CLAY MATRIX VARIABLE IN COLOR, ORANGE-BROWN TO GRAY TO GREEN TO BLACK TO PINK. CLAY LAYERS IN THE LOWER PART OF THE SECTION ARE VERY "NAVARRO-LIKE" IN APPEARANCE.
	LOWER CLAY		TYPICALLY A WHITE-GRAY CLAY WITH ORANGE-BROWN MOTTLES. MORE PLASTIC AND STIFF THAN BROWN CLAY. OCCURS PREDOMINANTLY ON THE EAST SIDE OF THE BASE. GREEN PLASTIC CLAY DESCRIBED IN RADIAN BORING LOGS FROM THE WEST PART OF THE BASE ALSO INCLUDED IN THIS LITHOFACIES.
	GRAVEL		VARIOUS COLORS BUT TYPICALLY BROWN TO LIGHT TAN, CLAY AND SILT CONTENT (MATRIX) <20%, CLASTS SUBROUND TO ANGULAR POORLY SORTED, CLAST SIZE IS COARSE SAND TO COBBLES. BOULDERS NOT RECOVERED BUT PROBABLY PRESENT. CLASTS ARE LIMESTONE OR CHERT.
	NAVARRO CLAY TRANSITION ZONE	TYPICAL WATER-BEARING LITHOFACIES	TYPICALLY A MN ZONE OF MIXED NAVARRO SILTY CLAY AND ALLUVIAL GRAVEL AND/OR SAND. GRAVEL <50%.
	NAVARRO CLAY AQUITARD		TYPICALLY HARD, PLASTIC, LAMINATED TO MOTTLED ORANGE-BROWN, BLUE-GRAY, GREEN-GRAY, AND DARK GRAY CLAY WITH ORANGE-BROWN SILTY PARTINGS, SOME FINE SAND LAYERS ARE PRESENT AND TYPICALLY OXIDIZED (DEEP RED-BROWN). CALCHE OCCURS OCCASIONALLY IN THE UPPER 6 FEET.

HYDROGEOLOGIC STRATIGRAPHY OF
THE ALLUVIAL AQUIFER SYSTEM
KELLY AIR FORCE BASE
SAN ANTONIO, TEXAS



Figure A-20. Legend for geologic profile of Site S-1 at Kelly AFB.

A.3 OPERATIONAL DATA

A.3.1 Temperature

RF energy was applied to the exciter electrodes and flowed outward to the ground electrodes. Soil temperatures were monitored throughout the 61 day treatment period during which RF energy was applied to the soil. Before treatment began, the soil throughout the treatment zone was at a temperature of approximately 20°C (68°F).

At the end of the treatment period, the soil temperature varied considerably throughout the revised design treatment zone. Figure 4 shows the electrode and thermowell layout for the SITE demonstration.

A.3.1.1 Temperatures at Ground Electrodes

The soil near the ground electrodes was gradually heated as RF energy flowed to the ground electrodes from the exciter electrodes. The soil temperatures near the center ground electrodes (A3, A4, A5, A6, C3, C4, C5, and C6) rose higher and faster than soil temperatures near the outer ground electrodes (A1, A2, A7, A8, C1, C2, C7, and C8). In addition, higher temperatures were measured in the shallow soils than in the deep soils.

Depth of 1 foot (0.3 meters) - Soil temperatures at a depth of 1 foot (0.3 meters) followed the same pattern for all ground electrodes but A4. In all ground electrodes but A4, the soil temperature gradually rose to a maximum of 80 to 96°C (176 to 205°F), which was reached near the middle of the treatment period. The temperature then decreased slightly to 62 to 78°C (144 to 172°F). The temperature of ground electrode A4 rose to 90°C (194°F) after an elapsed time of 45 days, decreased slightly, then increased to 112°C (234°F) by the end of the treatment period.

Depth of 12 feet (3.7 meters) - The temperature pattern at this depth is similar to the pattern observed at a depth of 1 foot (0.3 meters). The soil temperature rose to a maximum temperature of 68 to 99°C (154 to 210°F) near the middle of the treatment period. After reaching this peak, the temperature decreased slightly to 63 to 82°C (145 to 180°F).

Depths of 24 and 29 feet (7.3 and 8.8 meters) - In general, the temperatures in the ground electrodes at depths of 24 and 29 feet (7.3 and 8.8 meters) rose steadily throughout the treatment period. Maximum temperatures were reached at or near the end of the treatment period and ranged from 42 to 52°C (108 and 126°F) at 24 feet (7.3 meters) bgs and 31 to 34°C (88 to 93°F) at 29 feet (8.8 meters) bgs. The final temperatures at 29 feet (8.8 meters) bgs are only about 10°C (20°F) higher than the soil temperature before RF energy was applied.

A.3.1.2 Temperatures at Exciter Electrodes

The RF energy applied to the exciter electrodes progressed gradually from the surface to the lowest point of each exciter electrode. All exciter electrode temperature data fluctuated widely near the end of the treatment period.

Depth of 1 foot (0.3 meters) - Temperatures of 150°C (302°F) or greater were first consistently achieved 2 to 9 days after treatment began and were generally maintained throughout the remainder of the treatment period. Temperatures began to vary widely 38 to 61 days after treatment was initiated. Maximum temperatures of 330 to 1150°C (626 to 2102°F) were reached during this period.

Depth of 10 feet (3 meters) - Temperatures of 150°C (302°F) or greater were first consistently achieved 19 to 34 days after treatment began and were generally maintained for the remainder of the treatment period. Temperatures began to vary widely 45 to 58 days after treatment was initiated. Maximum temperatures of 725 to 1304°C (1337 to 2379°F) were reached during this period.

Depth of 19 feet (5.8 meters) - Temperatures of 150°C (302°F) or greater were first consistently achieved starting 20 to 32 days after treatment began and were maintained for the remainder of the treatment period. Temperatures began to vary widely 40 to 51 days after treatment was initiated. Maximum temperatures of 978 to 1330°C (1792 to 2426°F) were reached during this period.

A.3.1.3 Temperatures in Thermowells 1 and 2

As shown in Figure 5, TW1 and TW2 were in line with the exciter electrodes. Because TW2 is closer to the exciter electrodes, temperatures in TW2 were generally higher than temperatures in TW1. At 1 foot (0.3 meters) bgs, maximum temperatures in TW1 and TW2 were 103 and 129°C (217 and 264°F), respectively. At 12 feet (3.7 meters) bgs, maximum temperatures in TW1 and TW2 were 94 and 126°C (201 and 259°F), respectively. At 20 feet (6.1 meters) bgs, maximum temperatures in TW1 and TW2 were 69 and 117°C (156 and 243°F), respectively. At 24 feet (7.3 meters) bgs, maximum temperatures in TW1 and TW2 were 63 and 60°C (145 and 140°F), respectively. At 29 feet (8.8 meters) bgs, the maximum temperature for both TW1 and TW2 was 38°C (100°F).

A.3.1.4 Temperatures in Thermowells 3, 4, 5, and 6

As shown in Figure 5, TW3, TW4, TW5, and TW6 were located within the treatment zone between the exciter electrodes and the ground electrodes. Because TW3 was farther from the exciter electrodes than were TW4, TW5, and TW6, lower temperatures were measured in TW3.

Denth of 1 Foot (0.3 meters) The temperature in TW3 remained above 80°C (176°F) after Day 10. The temperatures in TW4, TW5, and TW6 remained above 100°C (212°F) after Days 17, 10, and 14, respectively. The temperature in TW5 remained above 150°C (302°F) from Day 25 through Day 46. Maximum temperatures for TW3, TW4, TW5, and TW6 were 105°C, 195°C, 243°C, and 181°C (221, 383, 469, and 358°F), respectively.

Depth of 12 Feet (3.7 meters) The temperature in TW3 remained above 90°C (194°F) after Day 20. The temperatures in TW4, TW5, and TW6 remained above 100°C (212°F) after Days 31, 21, and 15, respectively. Maximum temperatures for TW3, TW4, TW5, and TW6 were 111°C, 168°C, 210°C, and 206°C (232, 334, 394, and 403°F), respectively.

Death of 20 Feet (6.1 meters) At this depth, data were only collected from Day 44 through Day 53. Temperatures in these thermocouples fluctuated considerably during this period. Maximum temperatures for TW3, TW4, TW5, and TW6 were 87°C, 197°C, 234°C, and 205°C (189, 387, 453, and 401°F), respectively.

Denths of 24 and 29 Feet (7.3 and 8.8 meters) The temperatures in TW3, TW4, TW5, and TW6 at 24 and 29 feet (7.3 and 8.8 meters) bgs seem anomalous. At 24 feet (7.3 meters) bgs, maximum temperatures for TW3, TW4, TW5, and TW6 were 90°C, 90°C, 68°C, and 65°C (194, 194, 154, and 149°F). At 29 feet (8.8 meters) bgs, maximum temperatures for TW3, TW4, TW5, and TW6 were 81°C, 38°C, 36°C, and 39°C (178, 100, 97, and 102°F).

A.3.1.5 Temperatures in Thermowell 7

As shown in Figure 3, TW7 was located outside the treatment zone. The temperature patterns observed in TW7 were therefore similar to those in the ground electrodes, although, as expected, the temperatures were lower in TW7. At 12 feet (3.7 meters) bgs, the temperature rose to a maximum temperature of 62°C (144°F). The temperatures at 24 and 29 feet (7.3 and 8.8 meters) bgs rose gradually throughout the treatment period, reaching final temperatures of 40 and 30°C (104 and 86°F), respectively.

A.3.2 SVE System Operation

The SVE system was designed, operated, and monitored by B&RE. A log of SVE system operation was provided to the SITE Program. SVE operating conditions while RF power was being applied are summarized in Table A-16. After the heating period ended, the SVE system operation continued for approximately 2 months during the cooldown period. SVE operating conditions during cooldown are summarized in Table A-17.

Table A-16. Summary of SVE System Operation Conditions During RF Heating Period

Operating Parameter	Average Value	Minimum Value	Maximum Value
Inlet air flow rate	73 scfm (34 liters/s)	55 scfm (26 liters/s)	90 scfm (42 liters/s)
Mixed vapor flow rate	197 scfm (93 liters/s)	150 scfin (71 liters/s)	230 scfm (109 liters/s)
Inlet air pressure	79 psi (545 kPa)	44 psi (303 kPa)	94 psi (648 kPa)
Vapor temperature	149 °F (65 °C)	85 °F (29 °C)	170 °F (77 °C)
Mixed vapor temperature	115 °F (46 °C)	60 °F (16 °C)	145 °F (63 °C)
Ambient temperature	69 °F (21 °F)	45 °F (7.2 °C)	95 °F (35 °C)
Suction pressure	8.4 in H ₂ O (2.1 kPa)	7.0 in H ₂ O (1.7 kPa)	13 in H ₂ O (3.2 kPa)
Discharge pressure	15 in H ₂ O (3.7 kPa)	12 in H ₂ O (3.0 kPa)	18 in H ₂ O (4.5 kPa)

Table A-17. Summary of SVE System Operation Conditions During Cooldown

Operating Parameter	Average Value	Minimum Value	Maximum Value
Inlet air flow rate	55 scfm (26 liters/s)	30 scfin (14 liters/s)	76 scfm (36 liters/s)
Mixed vapor flow rate	182 scfm (86 liters/s)	60 scfm (28 liters/s)	250 scfin (118 liters/s)
Inlet air pressure	55 psi (379 kPa)	3 psi (21 kPa)	88 psi (607 kPa)
Vapor temperature	134 °F (57 °C)	78 °F (26 °C)	165 °F (74 °C)
Mixed vapor temperature	97 °F (36 °C)	76 °F (24 °C)	135 °F (57 °C)
Ambient temperature	77 °F (25 °C)	69 °F (21 °C)	95 °F (35 °C)
Suction pressure	7.5 in H ₂ O (1.9 kPa)	4.0 in H ₂ O (1.0 kPa)	14 in H ₂ O (3.5 kPa)
Discharge pressure	13 in H ₂ O (3.2 kPa)	4.0 in H ₂ O (1.0 kPa)	20 in H ₂ O (5.0 kPa)

The suction for the SVE system was provided by an air compressor that supplied compressed air to an inductor. The inlet air temperature and pressure were measured in the compressed air line leading to the inductor. The suction pressure and the vapor temperature were measured in the vapor collection manifold, upstream of the inductor. The mixed vapor flow rate, mixed vapor temperature, and discharge pressure were measured in the combined air stream (containing air from the compressor and vapors extracted from the soil) downstream of the inductors.

A.3.3 Dewatering System Operation

The dewatering system, which was designed and operated by B&BE, was installed in January 1993. Dewatering began on February 1, 1993 and continued during the remainder of pretreatment sampling, which was completed on February 6, 1993. B&RE has provided the SITE Program with a log of dewatering system operation from April 3, 1993 through August 23, 1993. This log indicates that 325,920 gallons (1,234 cubic meters) of groundwater were removed from the site between April 3, 1993 and August 23, 1993. It is not known whether the dewatering system was operated between pretreatment sampling and April 3, 1993.

IITRI believes that shallow groundwater led to the RFH system malfunction that caused high temperatures near the exciter electrodes and rather low temperatures near the ground electrodes. IITRI's explanation is that RF energy, like a conventional microwave, preferentially heats water (and other polar materials). They believe that the proximity of the groundwater to the exciter electrodes "shorted out" the RF energy and disrupted the heating patterns. Because the dewatering system was designed to prevent this type of problem, it appears that either the dewatering system was inadequate or IITRI underestimated the distance that must be maintained between the groundwater and the ends of the exciter electrodes. The exciter electrodes extended from the ground surface to 19.5 feet (5.94 meters) bgs. The results of groundwater level monitoring during the first 18 days of dewatering are presented in Table A-18. The results of groundwater level monitoring during the RF heating period are presented in Table A-19. Groundwater level monitoring locations are shown in Figure 5. All information regarding groundwater levels was provided by B&RE.

Table A-18. Groundwater Levels After Dewatering Was Initiated (Feet bgs)^a

Date	Well Number									
	PW03	DW01	DW02	DW03	MW09	MW10	MW11	MW12	PW04	
2/2/93	22.5	23.8	22.6	23.3	24.4	23.8	23.7	23.9	24.6	
2/2/93	22.8	**	26.0	**	**	23.9	23.8	**	35.4	
2/2/93	23.5	**	25.8	**	**	23.9	23.9	**	32.8	
2/2/93	23.1	**	**	**	**	**	**	**	**	**
2/2/93	23.5	**	**	**	**	**	**	**	**	**
2/3/93	23.8	29.8	28.3	24.2	24.4	24.0	24.1	26.3	35.0	
2/3/93	**	**	27.8	**	**	24.0	24.1	26.2	34.9	
2/4/93	23.7	30.0	27.8	**	**	24.0	24.4	26.1	**	
2/4/93	22.9	29.9	27.7	24.2	24.5	24.0	24.4	26.1	35.0	
2/4/93	23.8	29.7	28.0	**	**	24.0	24.5	26.1	**	
2/7/93	23.4	**	**	**	**	23.9	24.2	25.8	**	
2/7/93	23.5	**	**	**	**	**	**	**	**	**
2/8/93	23.6	**	**	**	**	**	**	**	**	**
2/8/93	23.4	**	**	**	**	**	**	**	**	**
2/9/93	22.9	**	**	**	**	24.1	24.5	24.2	**	
2/9/93	23.0	**	**	**	**	24.1	24.2	24.7	**	
2/9/93	23.1	**	**	**	**	**	24.3	25.0	**	
2/9/93	23.5	**	**	**	**	**	24.1	25.7	**	
2/10/93	20.6	**	**	**	**	24.2	24.2	24.1	**	
2/10/93	22.1	**	**	**	**	24.1	24.3	25.5	**	
2/11/93	23.3	**	**	23.7	**	24.1	24.2	25.7	**	
2/11/93	23.5	**	**	25.6	**	24.2	24.3	25.7	**	
2/12/93	24.8	**	**	**	**	**	24.3	26.8	**	
2/13/93	24.5	**	**	**	**	**	**	**	**	**
2/13/93	24.5	**	**	**	**	**	**	26.0	**	
2/15/93	22.6	**	**	**	**	**	**	**	**	**
2/16/93	24.4	**	**	**	**	**	**	**	**	**
2/16/93	24.6	**	**	**	**	**	**	**	**	**
2/18/93	24.7	**	**	**	**	**	**	**	**	**
2/19/93	24.7	**	**	**	**	**	**	**	**	**

^a Groundwater levels were measured in feet. To convert to meters, multiply by 0.3048.

** No groundwater level provided.

Table A-19. Groundwater Levels During RF Heating (Feet bgs)

Date	Well Number							
	DW01	DW02	DW03	MW09	MW10	MW11	MW12	PW04
4/29/93	30.6	27.6	26.5	25.0	24.7	**	26.6	32.9
5/8/93	**	**	**	24.9	24.1	**	25.6	**
5/10/93	**	**	**	24.5	24.3	24.4	26.1	
5/12/93	30.1	29.6	26.3	24.5	24.4	24.4	26.2	**

a Groundwater levels were measured in feet. To convert to meters, multiply by 0.3048.

** No groundwater level provided.

A.3.4 Electric Usage

An electric meter was installed and monitored by B&RE. Because the first two meters installed did not work correctly, electric usage was only monitored from April 26, 1993 through August 11, 1993. Based on the electric usage log for this period, the average power usage rate during the heating period was 58 kW and the average power usage rate during the cooldown period was 6.5 kW.

A.3.5 RF Emissions

The USAF contractor responsible for monitoring the RFH system did not supply RF emissions data from the IITRI demonstration to the SITE Program.

APPENDIX B

CASE STUDIES

B.1 VOLK AIR NATIONAL GUARD BASE (ANGB)

The first in situ field test of the IITRI RFH system was conducted at Volk ANGB in Wisconsin [1]. The treatment zone was located in a fire training pit and contained approximately 20 cubic yards (15 cubic meters) of sandy soil contaminated with organics, including waste oils, fuels, and solvents [at a depth of 7 feet (2 meters)]. The homogenous sandy soil present at Volk ANGB was considered an ideal medium for remediation by RFH.

RF power was applied to the treatment zone to heat the soil. The temperature at the center of the zone reached 100°C (212°F) after 2 days and approximately 150°C (302°F) after 8 days. Grab samples were taken on the ninth day and analyzed immediately. As shown in Table B-1, the test results indicated removal efficiencies of 90 percent or greater and the test was terminated.

Table B1. Results of Volk ANGB Test

Contaminant	Initial Concentration, mg/kg	Final Concentration, mg/kg	Removal Efficiency, Percent
Volatile Aromatics	210	0.9	99.6
Volatile Aliphatics	4200	2.8	99.3
Semivolatile Aromatics	250	2.3	99.1
Semivolatile Aliphatics	1660	9.5	94.3

Vapors rising from the treatment zone were captured and channeled to a vapor treatment system consisting of an air-cooled heat exchanger (for condensation of steam and contaminant vapors) followed by a separator (to remove the condensate from the vapor stream) and carbon adsorbers.

Grab samples were taken outside of the treatment zone to analyze the potential for contaminant migration into or out of the treatment zone. Contaminant concentrations in the soil surrounding the treatment zone were reduced by 75 percent or more. IITRI concluded that contaminants from outside the treatment zone were being volatilized and collected by the in situ RFH system. This conclusion was substantiated by radon tracer studies, which also indicated that contaminant migration occurred from outside regions into the treatment zone.

B.2 ROCKY MOUNTAIN ARSENAL (RMA)

The second in situ RFH field test was conducted at RMA, near Denver, Colorado [2]. The test zone contained approximately 60 cubic yards (50 cubic meters) of soil contaminated with organochloropesticides and organophosphorus compounds at concentrations up to 5,700 mg/kg and 3,900 mg/kg, respectively. Because these compounds have higher boiling points than the contaminants present at Volk ANGB, target treatment conditions were 250°C (482°F) for 72 hours.

A 40-kW RF power source delivered approximately 18,000 kWh of energy to the test zone over a 37day period. The soil in the test area, which consisted of sandy clays and clayey sands, was not heated uniformly. Portions of the test zone were heated to over 350°C (662°F), while other portions were heated to only 100°C (212°F). In areas that reached temperatures in excess of 250°C (482°F), organochloropesticide destruction efficiencies of 97 to 99 percent were achieved. Destruction efficiencies were generally lower in areas that did not reach 250°C (482°F).

The vapors produced during heating were treated in a vapor treatment system which removed both the VOCs and SVOCs. A total of 1,545 gallons (5.8 cubic meters) of water was produced during the heating. This water was recovered in the vapor treatment system, and was ultimately sent to Pond A at the RMA for storage.

B.3 REFERENCES

1. Dev, H., J. Enk, G. Sresty, J. Bridges, and D. Downey. In Situ Decontamination by Radio-Frequency Heating – Field Test. Prepared by IIT Research Institute for Air Force Engineering & Services Center, September 1989.
2. Roy F. Weston, Inc. Rocky Mountain Arsenal In Situ Radio Frequency Heating/Vapor Extraction Concept Engineering Report, November 1992.

APPENDIX C

VENDOR CLAIMS

NOTE: This appendix was prepared by IITRI. Claims and interpretations of results in this Appendix are those made by the vendor and are not necessarily substantiated by test or cost data. Many of IITRI's claims regarding cost and performance can be compared to the available data in Section 4, Section 3, and Appendix A of this ITER.

C.1 INTRODUCTION

The in situ radio frequency (RF) heating process utilizes electromagnetic energy in the radio frequency band to heat soil rapidly without injection of heat transfer media or on site combustion. The process can be used to heat soil to a temperature range of 150-200°C. A modification of the process, called EM heating, based on the use of 60-Hz alternating current (AC) can be used to heat soil to a temperature range of 80 to 90°C. The contaminants are vaporized along with native soil moisture. The gases and vapors formed upon heating the soil are recovered for on site treatment by means of a gas collection system.

In situ heating is performed by energizing an array of electrodes emplaced in bore holes drilled through the soil. The process can be used for the removal of organic chemicals which exhibit reasonable vapor pressure (5 to 10 mm of Hg) in the treatment temperature range.

The feasibility of the in situ RF soil decontamination process was first demonstrated at a site of a jet fuel spill (1). Three additional field experiments or demonstrations have been conducted subsequently at Rocky Mountain Arsenal (RMA), Kelly Air Force Base (AFB), and Sandia National Laboratory (SNL). The Kelly field test was conducted under the EPA SITE program, and is the subject of this report. IITRI could not complete soil heating at the Kelly field test due to unanticipated shallow groundwater at the site. A larger demonstration of the technology has recently been completed (April, 1995) at SNL as a part of the Thermal Enhanced vapor Extraction System (TEVES).

It must be noted that the SITE program evaluation and the scale-up of the technology performed by the EPA are based on the incomplete demonstration at Kelly AFB. Cost analysis of the technology reported in this document is also based on the EPA's scale-up and design. IITRI disagrees with some of the assumptions made during the scale-up and design because of a number factors including scale-up based on an incomplete soil heating test at Kelly AFB, limitations concerning the longitudinal propagation of RF energy along the length of the scaled-up electrode array, use of a 10-in. hollow stem auger for the drilling of all electrode (3 or 4 in.) holes, and the lack of an energy balance. Our scale-up designs that were based on IITRI's knowledge and experience with the application of the RF technology have been summarized elsewhere (2)

This section contains a brief description of the RF heating process, a summary of results obtained during field tests and reasons for the experienced difficulties at Kelly AFB, and IITRI's current plans for further development and commercialization of the AC and RF heating technologies.

C.2 PROCESS DESCRIPTION

The RF soil decontamination process is a two-step process which operate simultaneously once the average temperature of the soil exceeds 50°C. These steps are: heating of the soil, and vaporization and recovery of the contaminants.

In the first step of the process, the soil is heated to elevated temperatures (80 to 90°C for AC heating and up to 200°C or higher for RF heating) by means of an electrode array inserted in bore holes drilled through the soil. Selected electrodes are specially designed to permit the application of RF power while collecting vapors by application of a vacuum down hole. Figure C-1 is an artist's illustration of the process as utilized during the TEVES demonstration at SNL. Both AC and RF heating were used at SNL. Power to the electrode array is provided by means of a variable-tap transformer or power amplifier designed to generate RF energy in the frequency range of 1 to 10 MHz.

The vapor collection system is an integral part of the electrode array since vapor collection points are physically integrated and embedded in the array. A vapor containment barrier is used to prevent fugitive emissions, and provides thermal insulation to prevent excessive cooling of the near surface zones.

Prior laboratory and field experiments (1-5) have shown that high boiling contaminants can be boiled out of the soil at much lower temperatures than their actual boiling point. This occurs due to two

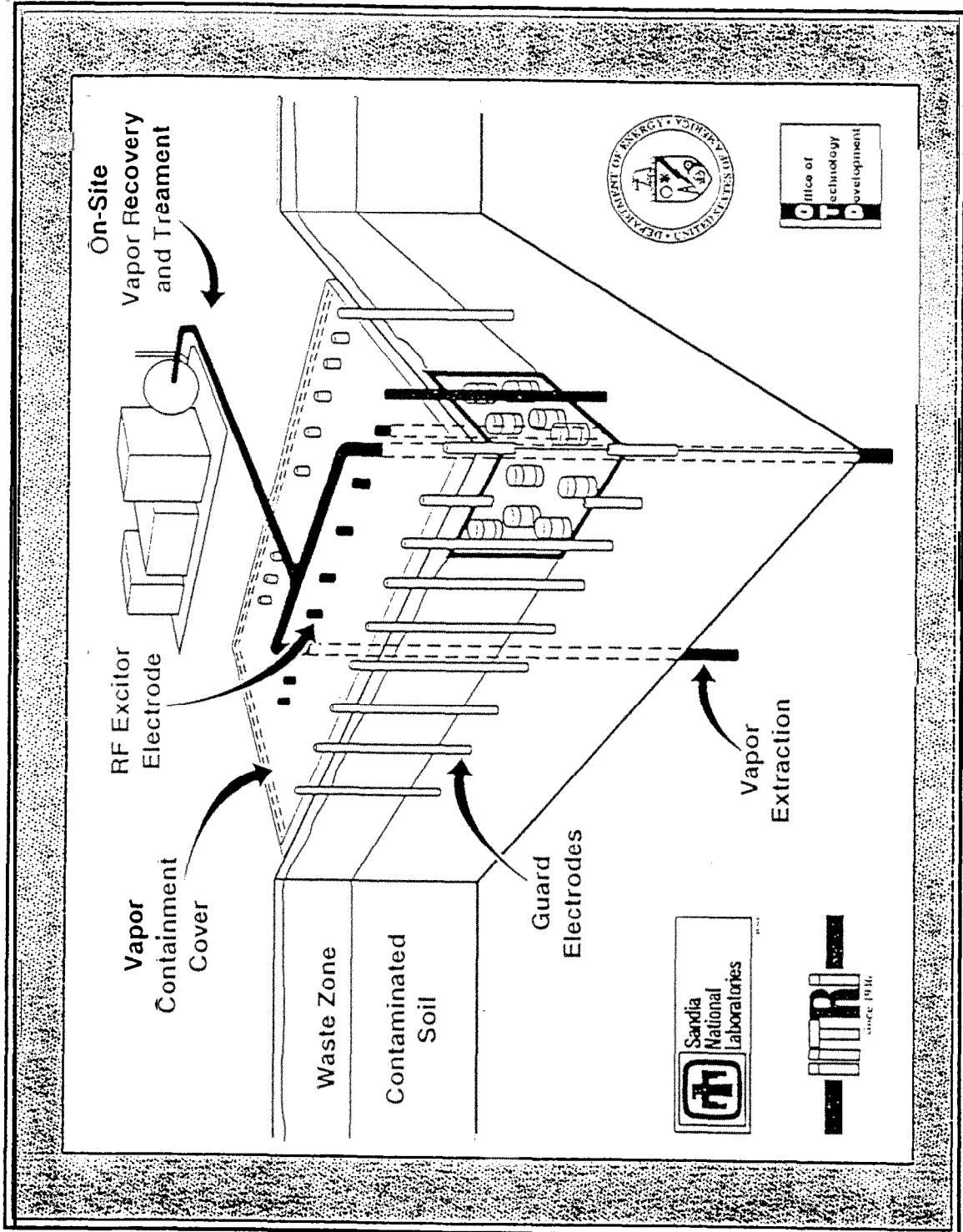


Figure C-1. Illustration of TEVES demonstration at SNL.

reasons: first, the presence of an autogenously established steam sweep helps to improve vaporization rate of such high boiling materials; second, the long residence time in situ permits significant removal, albeit at a rate which is slower than that obtainable in above ground thermal treatment systems. Another phenomenon which operates during in situ heating is the development of effective permeability to gas flow. The increase in permeability is confined to the heated zone, thus creating a preferred path of gas and vapor flow towards the soil surface.

The second step of the process is the collection, recovery, and on-site treatment of the vapors and gases formed by heating of the soil. The collected waste gases are transported to an on-site treatment system. Various treatment techniques based on condensation, carbon adsorption, spray chambers, combustion, and catalytic oxidation have been used during previous field tests.

There are several important advantages of the in situ AC or RF soil decontamination process. These are: true in situ treatment minimizes earth removal, excavation etc., thereby minimizing attendant hazards related to odors, fugitive emissions and dust. Only 0.5 to 1.5 percent of the treated volume will require removal for the formation of the electrode bore holes. There is no on site combustion; a concentrated gas stream containing air, water and contaminant vapors is produced which is treated on site; the process equipment may be trailer mounted and mobile.

Some of the limitations of the process are: unable to treat metals, salts, and inorganic pollutants; if large buried metal objects are present in portions of the treatment zone then the applicability of the process may be limited to zones free of such objects. Another important limitation for the RF heating process concerns with heating saturated zones with rapidly flowing groundwater such as the one noted at Kelly AFB. Water absorbs a considerable amount of energy for its heating and evaporation. If water moves rapidly through the heating zone, it carries the heat away and the array continuously and preferentially supplies energy to heat and evaporate water from bottom of the electrodes. This can result in peaking of the RF energy at the tips of electrodes and interfere with heating. It is necessary to control the movement of the groundwater through the soil matrix by the installation of impermeable liners and/or pumping wells prior to the application of RF heating process. If site conditions preclude groundwater control, only AC heating should be considered for such sites. At such sites energy consumption will be high, proportional to heat loss due to flowing water but unlike the RF process, the AC heating system should be free of anomalous hot spots that force a shutdown of the process.

C.3 TREATABILITY STUDIES

Several treatability studies on various types of contaminants have been performed. These studies were done in the laboratory to determine the optimum temperature and treatment time for different types of contaminants found in different soil types. The treatability studies have focussed on chlorinated solvents, volatile aromatic hydrocarbons such as benzene, toluene, etc. (BTEX), petroleum hydrocarbons (TPH), phenols, chlorinated biphenyls (PCBs), and polynuclear aromatic hydrocarbons (PAHs).

The results of various treatability studies are summarized in Table C-1. Detailed information on any given study is available in the cited reference. The data summarized in table 1 indicates that suitable treatment conditions can be found under which high removals of most of the tested contaminants occurs. The data further confirm that high boiling compounds need not be heated to their boiling points in order to achieve high removals. As an example consider the PAHs of various molecular weight (viz. number of fused rings). The more volatile PAHs under consideration boil in the temperature range of 280-300°C, while the less volatile ones boil at temperatures above 500°C. Yet the results show that significant removals of PAHs boiling up to 400°C can be achieved in the temperature range of 200 - 230°C. Similar results were obtained for Aroclor 1242. The results show that the concentration of Aroclor 1242 can be reduced to below 25 ppm when the soil is treated at 230°C.

C.4 FIELD EXPERIMENTS

A total of four field experiments/demonstrations have been completed to date. Table C-2 provides a summary of the field experiments and the results. Since RF and AC heating process are innovative soil treatment processes under development, we have attempted to scale-up the process during these experiments to heat increasingly larger volumes of soil, and to extend the applicability of the process to different types of soil and contaminants, and to treat soils to a greater depth. The field experiments at Volk Air National Guard Base (Volk), RMA and SNL have been successfully completed. Since the SNL test was only concluded in April, 1995, data on the concentrations of contaminants was not available at the time of preparation of this document. A summary of the experience gained during the Kelly demonstration is provided below.

C.4.1 Kelly Demonstration

The demonstration conducted at Kelly APB resulted in incomplete heating of the target soil volume because of a shallow and rapidly moving groundwater through the treatment zone. Prior

Table C-1. Summary of Pilot Scale Experiments

Type of Soil	Source of Soil	Source	Contaminants		Treat. Temp., °C	% Contaminant Removal	IITRI Proj. No.	Reference	Comments
			List	Init. Conc. (ppm)					
Sandy	Volk ANGB	Spike	PCE CBZ	0.2 - 35 n.d. - 36	128 - 159	98.4 - 100	C06600	1	Spike evaporation caused low initial conc.
Sandy	Volk ANGB	Field	<u>Jet Fuel</u> Aromatics Nonaromatic Pentadecane		155	>95 90 - >99 75 - >95	C0660	1	Steam sweep enhanced removal of the high-boilers.
Sandy	Tyndall AFB	Spike	Aroclor 1242	1,000	150 - 300	48 - 99.7	C06600	1	High Aroclor removal and poor mass balance at high temps.
Clayey	Carlswell AFB	Field	<u>Jet Fuel</u> Aromatics Nonaromatics		90 - 165	66 - 83 70 - 87	C06691	2	Residual conc. was a few ppm.
Clayey	Kelly AFB	Field	Sludge Aromatics Nonaromatics	200 1,000	140 - 153	87 - 98.8 94 - 98.8	C06691	2	Experiments were conducted with steam sweep.
Sandy/clayey	Chicago	Spike	Phenol PCP Phenanthrene	1,000 1,000 1,000	110 - 200	74 - >99.7 42 - >90.3 60- >99.1	C06693 C022	4	Higher temperatures and steam sweep helped removal of PCP phenanthrene.
Clayey	Wood Preservative Site	Field	PAHs 2-ring 3-ring 4-ring S-ring	6 - 50 7 - 60 250- 410 10-27	200 - 230	84 - >97 61 - >97 7- 37 8 - 35	C06730	5	Mass balance data available.
		Field Spiked	PCBs Aroclor 1242	1070- 1250	200 - 230	96 - 99	C06730	5	Mass balance data available.

Table C-2. Summary of Field Experiments/Demonstrations

	Volk	RMA	Kelly	SNL
Target Soil Volume, cu. yds.	19	30'	122	550
Array Dimensions, A.	5' x 10'	6' x 14'	10' x 17.5'	20' x 50'
Depth of Treatment, ft.	7'	3' x 13'	23'	18'
Target Temperature, °C	150'	250	150	150
Soil Type	Sandy	Clay	Silt, Clay and Cobbles	Silty Sand
Site Description	Fire Training Pit	Waste Basin	Sludge Disposal Pond	Chemical Waste Landfill
Major Contaminants	Solvents, Jet Fuel	Organochloro Pesticides	TPH	Solvents, TPH, Heat Transfer Fluids
Treatment Duration, days	13	35	60	67
Heating System	RF	RF	RF	AC and RF
Summary of Results	Removed >99% of VOCs and > 94% of svocs	Removed >99% endrin, aldrin and dicldrin. Removed >98% isodrin	Heated only 44 cu. yds. to target temperature. Removed 95% TPH from heated zone and 60% from the total revised treatment zone	Vapor concentrations for high boiling hydrocarbons increased significantly. Soil concentration data not available at this time.

characterization data for the site precluded any groundwater in the treatment zone. Hence, the system design did not consider the effect of groundwater. However, shallow groundwater at a depth of less than 25 ft. was encountered during drilling for electrode placement. The following steps were taken to mitigate the effect of groundwater.

1. Dewatering wells were installed to pump as much water as possible and to attempt to maintain the water level below 25 ft.

Installation of center (excitor) row electrodes was delayed to see the results of the dewatering system.

2. The length of the exciter electrodes was reduced to 20 ft. from their fabricated length of 24 ft. New, shorter excitor electrodes were fabricated in the field. With the shortened exciter electrodes, shortening of the ground electrode was indicated, but due to time and cost constraints it was decided to leave the long (29 ft) ground electrodes in place.
3. The bottom tips of the new excitor electrodes were modified to have spherical bottoms to partially mitigate the effects of excess currents.

Despite the above corrective steps, IITRI was not able to complete soil heating as planned. As per our interpretation of the data, some time during the second half of the 9-week test period, applied RF energy concentrated towards the tips of the excitor electrodes causing their progressive melting. In fact, we were not able to increase the average temperature of the two outer rows of electrodes during the last two weeks of the test period. We were able to recover a total of only a few feet of the excitor electrodes with the rest having melted prior to termination of the test period. Interpretation of the electrical properties of the array indicates that the array input impedance changed irregularly after May 3, 1994 or the 30th day after heating started. These changes became even more drastic and irregular after May 18th. Melting point of copper was first exceeded in the center row of electrodes sometime between May 19 and 20. This indicates that only 45 days out of the total 61 day test period were effective (6).

As a result of the melting of excitor electrodes, only 44 cu. yds. of the 122 cu. yds. of soil from the revised design volume was heated to the target temperature. The soil near the ground electrodes never reached target temperatures. Since ground electrodes were used as collection wells, inadequate heating resulted in ineffective effluent collection, as noted by the EPA, and condensation of some of the contaminants migrating from outside regions in their vicinity. As a result, the concentrations of a number of contaminants increased in this region. The data prepared by EPA shows that the concentrations of some of the contaminants increased by several hundred percent. Since the pre- and

post-test concentrations were in the range of a few ppm or lower, it is easy to see large percentage increases with condensation of even small quantities of contaminants. For example, acetone, whose concentration increased by the largest value of 1073% in the revised treatment zone, had concentrations in the range of .11 and .38 ppm in the pre-test samples and .12 to 30.1 ppm in the pos-test samples. Similarly, methyl ethyl ketone, whose concentration increased by 683 % had a concentration range of 0.04 to 0.11 ppm in the pre-test samples and 0.08 to 12.7 ppm in the post-test samples.

IITRI took into account lessons learned from the Kelly demonstration and performed a subsequent larger experiment at SNL as part of the TEVES demonstration. The TEVES demonstration heated the entire contaminated site to avoid concerns associated with the migration of contaminants from the unheated regions. The effluent collection wells were moved from the ground row of electrodes to excitor electrodes to remove contaminants from the hottest regions and thus to avoid contaminant condensation. The test site also did not have shallow ground water.

C.5 CURRENT STATUS AND FUTURE PLANS

The RF heating process is currently under development for soil decontamination. The recently completed field experiment at SNL is the first large-scale demonstration of the RF heating technology. It is IITRI's opinion that additional development and demonstrations are necessary before the technology can be considered to be commercial. IITRI has equipment necessary to perform large-scale demonstrations and treat soil volumes of 1,000 cu. yds. or more. A sound design for treating large volumes of soil such as the one considered by the EPA can be developed based on the results of our field experiments, and this task must precede any cost evaluation.

The scale-up, design, and cost estimates developed by the EPA and discussed in this document were developed based on an incomplete heating test and a number of assumptions, and as a result, have a number of drawbacks.

The AC heating process has been used by IITRI and our licensees for heating oil wells for a number of years. The AC heating process for soil decontamination is a modification of existing technology, and has been demonstrated at SNL. IITRI is currently offering full-scale soil treatment using the AC heating process through its wholly owned subsidiary, Technology Commercialization Corporation.

C.6 REFERENCES

1. Dev, H., Enk, J., Sresty, G., Bridges, J. In Situ Decontamination by Radio Frequency Heating-Field Test. IIT Research Institute. Final Report CO6666/CO6676. Prepared for USAF, HQ AFESC/RDV, Tyndall AFB, Fl, May 1989.
2. Dev, H., and G. Dubiel. Optimization of Radio Frequency (RF) In Situ Soil Decontamination Process. Draft Final Report, IITRI Project No. C06691. ANL Contract No. 83482402. June 1990.
3. Dev, H., J. Bridges, G. Sresty, J. Enk, N. Mshaiel, and M. Love. Radio Frequency Enhanced Decontamination of Soils Contaminated with Halogenated Hydrocarbons. EPA/600-2-89/008, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1989.
4. Sresty, G.C., Dev, H., Gordon, S. M., and Chang, J. Methodology for Minimizing Emissions by Remediation of Environmental Samples Containing Wood Preserving Chemicals, Draft Final Report, IIT Research Institute. U.S. EPA Contract No. 69-D8-0002, Work Assignment No. 22, IITRI Project No. CO6693CO22.
5. Sresty, G., Dev, H., *Chang*, J., and Houthoofd, J. In Situ Treatment of Soil Contaminated with PAHs and Phenols. Presented at and to be published in the proceedings of the International Symposium on In Situ Treatment of Contaminated Soil and Water, Air and Waste Management Association, February 4-6, 1992, Cincinnati, Ohio.
6. Radio Frequency soil Decontamination Demonstration Project, Site S-1, Kelly AFB, Texas. Draft Final Report. IITRI Project No. C06781, Halliburton NUS Sub-contract No. GCKF-92-3688-002, September 1994.