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UNITED STATES AIR FORCE
ARMSTRONG LABORATORY

Demonstration of Radiofrequency Soil Decontamination: Volume II of III

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NOTICES

This report has been reviewed and is approved for publication.

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14. Abstract The Air Force Armstrong Laboratory, Tyndall Air Force Base, Florida, has supported the research and development of Radio Frequency Soil Decontamination. Radio frequency soil decontamination is essentially a heat-assisted soil vapor extraction process. Site S-1 at Kelly Air Force Base, Texas, was selected for the demonstration of two patented techniques. The site is a former sump that collected spills and surface runoff from a waste petroleum, oils, and lubricants and solvent storage and transfer area. In 1993, a technique developed by the ITT Research Institute using an array of electrodes placed in the soil was demonstrated. In 1994, a technique developed by KAI Technologies, Inc. using a single applicator placed in a vertical borehole was demonstrated. Approximately 120 tons of soil were heated during each demonstration to a temperature of about 150 degrees Celsius.

15. Subject Terms Radio Frequency Soil Heating, Soil Vapor Extraction

Security Classification of			19. Limitation of Abstract	20. # of Pages	21. Responsible Person (Name and Telephone #)
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PREFACE

This report was prepared by Halliburton NUS Environmental Corporation, 800 Oak Ridge Turnpike, Oak Ridge, TN 37830 under contract F33615-90-D-4011 for the Armstrong Laboratory Environics Directorate (AL/EQW) (formerly the Air Force Engineering and Services Center), Tyndall AFB, FL 32403-5323.

This final report summarizes the project's Phase I efforts for a field demonstration of the IIT Research Institute's (IITRI) tri-plate capacitor and the KAI Technologies, Inc.'s (KAI) antenna radio frequency heating (RFH) techniques for the enhancement of soil vapor extraction (SVE) for the in situ decontamination of soils.

The work was performed between June 1992 and December 1994. The AL/EQW technical project officers were Mr. Paul F. Carpenter (during the initial stage of the project) and Capt Jeffrey A. Stinson (during the latter stage of the project).

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EXECUTIVE SUMMARY

The United States Air Force developed the Installation Restoration Program to assess past hazardous waste disposal and spill sites and prepare remedial actions consistent with the National Contingency Plan for those sites that pose a threat to human health or the environment. Within that program the Site Remediation Division of the Environics Directorate of the Air Force's Armstrong Laboratory at Tyndall AFB, Florida, has supported the research and development of Radio Frequency Soil Decontamination.

Armstrong Laboratory was sufficiently encouraged by the early test results in sandy soils at Tyndall AFB, Florida, and Volk Field, Wisconsin, to pursue larger-scale demonstrations in tight soils that are more difficult to treat. In September 1991, the Air Force Center for Environmental Excellence at Brooks AFB, Texas, contracted Halliburton NUS Environmental Corporation (now Brown & Root Environmental) to conduct pilot scale demonstrations of two different, patented, radio frequency heating techniques at Site S-1 at Kelly AFB, Texas.

The project was divided into three phases the Preplanning Phase, Phase I, and Phase II. The Preplanning Phase, completed in September 1992, included literature review, conceptual cost estimations, design plans and specifications preparation and review, and publication of a final report documenting the results. Phase I included two integrated pilot tests and the preparation of this final technical report evaluating the results of Phase I and the conceptual planning of Phase II. Phase II will include the complete planning and design of a full-scale commercial demonstration of radio frequency soil decontamination.

Radio frequency soil decontamination is essentially a heat-assisted vapor extraction process. Radio frequency energy applied to the soil causes polar molecules, including water and many organic compounds, to vibrate. This vibrational energy is lost as heat. The resulting rise in soil temperature vaporizes both water and contaminants, which may then be removed by application of a vacuum. Extracted vapors may be treated by a variety of methods, depending on the site and the nature of the contaminants. Vapors extracted during the demonstrations at Site S-1 were burned in a flare.

Two types of radio frequency soil heating were demonstrated at Site S-1 from January to August 1993 and 1994. In 1993, a technique developed by the IIT Research Institute that uses a series of exciter and ground electrodes placed in the soil was demonstrated. This technique was tested previously at Air Force sites. In 1994, a technique developed by KAI Technologies, Inc. which uses an antenna-like device that may be placed in a vertical or horizontal borehole was demonstrated. Halliburton NUS Environmental Corporation provided site preparation services, the vapor extraction system, and supervised and coordinated all other aspects of the demonstrations.

Armstrong Laboratory, Kelly AFB, and the US Department of Energy have contributed funds and guidance for the work completed to date which includes the Preplanning Phase and Phase I. In addition, the Phase I demonstrations are part of the US Environmental Protection Agency's Superfund Innovative Technology Evaluation Program.

Halliburton NUS Environmental Corporation concludes that data gathered during the pilot demonstrations is invaluable to the development of radio frequency heating for the enhancement of soil vapor extraction and can be used to design a commercial scale system and implement remedial activities in accordance with United States Air Force procedures. From lessons learned during the Site S-1 demonstrations, criteria for technology implementation have become apparent that allow the selection of a site better suited to the unique physical and chemical phenomenon inherent in the process. To date only six field tests have been completed. These tests have addressed situations with a wide variance of soil and contaminant characteristics. A phased approach is recommended which would include more demonstrations to plug data gaps and define unknowns followed by commercial scale application. A smaller site with a simpler (more homogenous) soil and contaminant matrix, relative to Site S-1, would simplify the evaluation of results and better define technology applicability.

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ACRONYMS AND ABBREVIATIONS

AC	Alternating Current
AFB	Air Force Base
AFCEE	Air Force Center for Environmental Excellence (Brooks AFB)
AFOSH	Air Force Occupational Safety and Health
BTEX	Benzene, Toluene, Ethylbenzene, Xylene
BTU	British Thermal Unit
CAMU	Corrective Action Management Unit
CAT/OX	Catalytic Oxidation
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
CI	Confidence Interval
DC	Direct Current
DCE	Dichloroethene
DNAPL	Dense Non-Aqueous Phase Liquid
DOD	Department of Defense
DOE	Department of Energy
DRO	Diesel Range Organics
EPA	Environmental Protection Agency
EPCF	Environmental Process Control Facility
ERMO	Environmental Restoration Management Operations
FCC	Federal Communications Commission
FFS	Focused Feasibility Study
FID	Flame Ionization Detector
FM	Frequency Modulation
FS	Feasibility Study
GC	Gas Chromatograph
HNUS	Halliburton NUS Corporation
Hz	Hertz (cycles per second)
IIT	Illinois Institute of Technology
IITRI	Illinois Institute of Technology Research Institute
IRP	Installation Restoration Program
IRPIMS	Installation Restoration Program Information Management System
ISM	Industrial, Scientific, and Medical (radio frequencies)
IWTP	Industrial Waste Treatment Plant
KAI	KAI Technologies, Incorporated
kW	Kilowatt
kW/hr	Kilowatt-hour
LEL	Lower Explosive Limit

ACRONYMS AND ABBREVIATIONS (CONTINUED)

NAPL	Nonaqueous Phase Liquids
NCP	National Contingency Plan, or
	National Oil and Hazardous Substances Pollution Contingency Plan
NGVD	National Geodetic Vertical Datum
NIOSH	National Institute for Occupational Safety and Health
NUS	Halliburton NUS Environmental Corporation
O&M	Operation and Maintenance
ODC	Other Direct Costs
OSHA	Occupational Safety and Health Administration
OVA	Organic Vapor Analyzer
PCE	Tetrachloroethene or Perchlororethene
PFD	Process Flow Diagram
POL	Petroleum, Oil, and Lubricants
PPE	Personal Protective Equipment
PQL	Practical Quantitation Limit
PVC	Polyvinyl Chloride
R&D	Research and Development
RF	Radio Frequency
RFH	Radio Frequency Heating
RI	Remedial Investigation
SA-ALC	San Antonio Air Logistics Center
SAIC	Science Applications International Corporation
SCFM	Standard Cubic Feet per Minute
SITE	Superfund Innovative Technology Evaluation
SM	Site Manager
SSO	Site Safety Officer
SVE	Soil Vapor Extraction
SVOC	Semivolatile Organic Compound
TACB	Texas Air Control Board
TCLP	Toxic Characteristic Leaching Procedure
TNRCC	Texas Natural Resources Conservation Commission
TOC	Total Organic Carbon
TPH	Total Petroleum Hydrocarbons
TRPH	Total Recoverable Petroleum Hydrocarbons
USAF	United States Air Force
VOC	Volatile Organic Compound
VT	Vapor Treatment
W	Watt (s)

1.0 INTRODUCTION

1.1 BACKGROUND

The objective of the United States Air Force (USAF) Installation Restoration Program (IRP) is to assess past hazardous waste disposal and spill sites at USAF installations and develop remedial actions consistent with the US Environmental Protection Agency (EPA) National Contingency Plan (NCP) for those sites that pose a threat to human health and the environment. The development, testing, and demonstration of innovative restoration technologies are important phases of the IRP under the direction of the Site Remediation Division of the Environics Directorate (AL/EQW) of the USAF's Armstrong Laboratory at Tyndall Air Force Base (AFB), Florida.

Site S-1 (Figure 1-1) at Kelly AFB, Texas, was selected by Armstrong Laboratory for a Radio Frequency (RF) Soil Decontamination Demonstration. The site formally served as an intermediate storage and transfer area for wastes to be reclaimed off-base. The wastes included mixed solvents and petroleum, oils, and lubricants. Inadvertent spills during this operation resulted in soil and groundwater contamination. Halliburton NUS (HNUS) conducted a remedial investigation at the site to determine the nature and extent of soil and groundwater contamination (HNUS, 1994). The general types of organic compounds found in soil samples and common examples of each type are shown below:

Types of Organic Compounds	Examples
Volatile aromatics	Acetone, chlorobenzene
Chlorinated aliphatic volatiles	Methylene chloride, trichloroethane
Phthalate esters	Bis(2-ethylhexyl)phthalate
Polychlorinated biphenyls	Aroclor-1260
Polynuclear aromatic hydrocarbons	Benzo(a)anthracene, pyrene

Groundwater beneath the site contains many of the same contaminants. The variety of contaminants, while presenting a remedial challenge, offers an interesting opportunity for a technology demonstration.

This project report will summarize and document the project's Phase I efforts for a field demonstration of the IIT Research Institute's (IITRI) tri-plate capacitor and the KAI Technologies, Inc.'s (KAI) antenna radio frequency heating (RFH) techniques for the enhancement of soil vapor extraction (SVE) for the in-situ decontamination of soils.

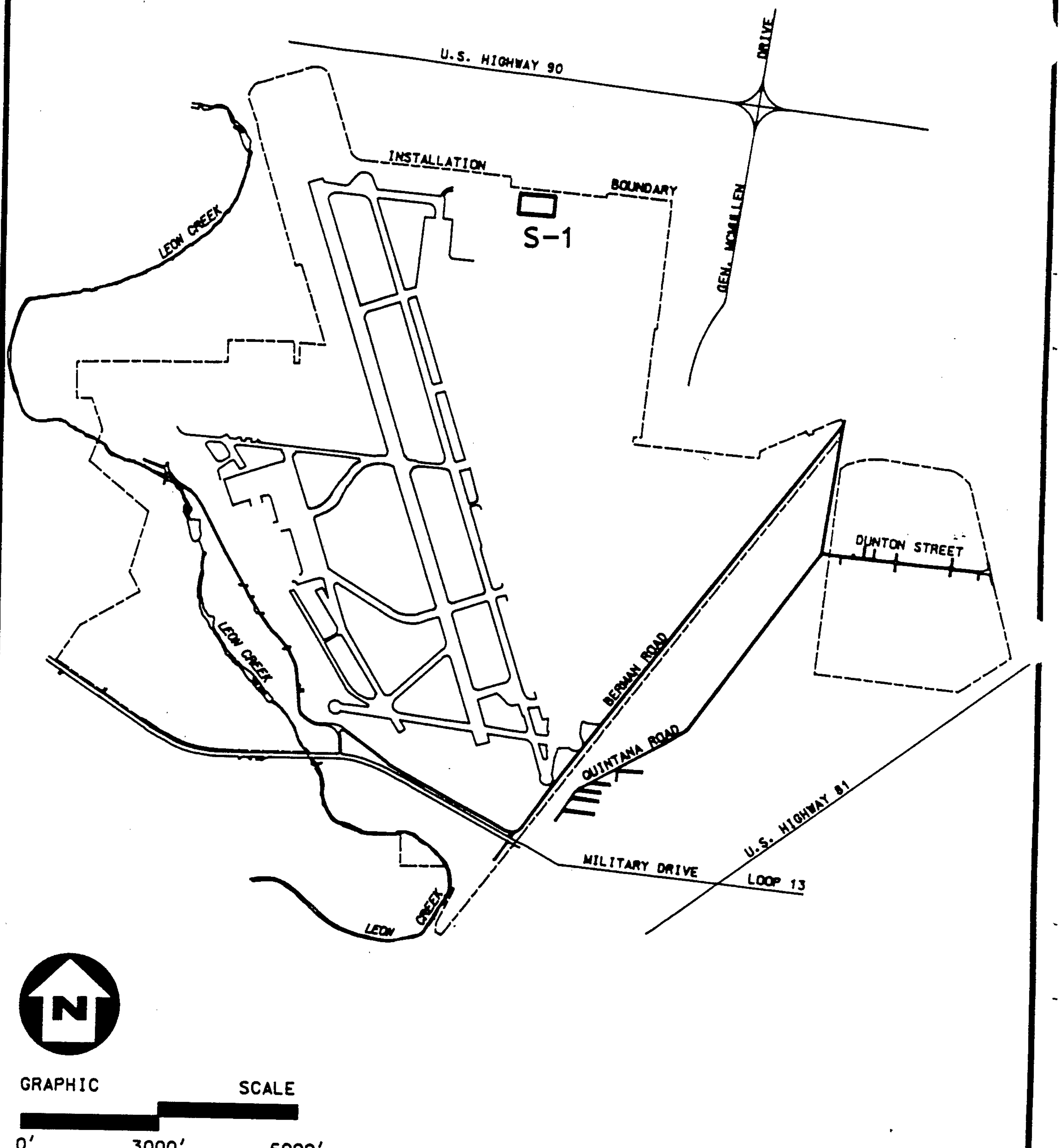


FIGURE 1-1

HALLIBURTON NUS
Environmental Corporation

TITLE

SITE S-1 LOCATION MAP
RF DEMONSTRATION
KELLY AIR FORCE BASE
SAN ANTONIO, TEXAS

DRAWING NO. 3688G001

DATE 4-30-92

1.2 AUTHORITY

HNUS was contracted by the Air Force Center for Environmental Excellence (AFCEE) to perform an RF Soil Decontamination Demonstration at Kelly AFB under the direction of the AL/EQW. Notice to Proceed was issued on September 28, 1991. The project was divided into three phases the Preplanning Phase, Phase I, and Phase II. The Preplanning Phase, completed in September 1992, included literature review, conceptual cost estimations, design plans and specifications preparation and review, and publication of a final report documenting the results. Phase I, complete with the final publication of this report, included two integrated pilot demonstrations, an evaluation of the results, and the conceptual planning of Phase II. Phase II, planned for 1995, will include the complete planning and design of a commercial scale system for RF soil decontamination.

1.3 OBJECTIVES OF PROJECT

The primary objectives of the project are as follows: (1) to broaden the proven range of RF technology applicability in clayey soil and (2) to more accurately assess the implementation requirements of commercial-scale systems. Secondary purposes to be addressed during the demonstration project include validation of scale-up parameters, the use of electrodes as vapor recovery vents, evaluation of vertical and horizontal transport of contaminants through soil, and the removal of semi-volatile organic compounds (such as phthalates) from soil.

Project results and evaluations will be documented in technical reports at the end of each Phase. This report for Phase I includes the following:

(a) Data gathered during the two pilot tests,
(b) Results of the evaluation of that data,
(c) A summary of lessons learned during the Preplanning Phase and Phase I,
(d) Recommendations for design/operational modifications to facilitate Phase II,
(e) Comparison of the two different techniques,
(f) An up-dated cost projection for Phase II,

This report is divided into nine sections and 18 appendices which document all design, field implementation, and evaluation activities and include requirements from the SOW as listed above. Sections 2 through 9 contain the HNUS evaluation of the demonstrations and conceptual design and cost information for a full-scale test. Appendices A and B contain reports from IIT and KAI and operational data from the two demonstrations.

1.4 PROJECT HISTORY

RF energy causes polar molecules in dielectric materials to vibrate, and the resulting mechanical energy is lost as heat. Early applications included industrial drying and the medical process known as diathermy. Radio frequency-enhanced petroleum recovery from oil shale and tar sands was demonstrated in the 1970s. Field tests proved the feasibility of heating rock formations to temperatures of 200° to 400° Celsius (C) (Dev et al, 1989). In 1984 the USAF began the research and development of RFH for in-situ soils decontamination that has led to this field demonstration.

IITRI applied the technique to the decontamination of soils containing hazardous chemicals in EPA-funded laboratory tests. Bench and pilot scale tests demonstrated the need for an in situ field demonstration. During a field test of the IITRI method in November 1988 at Volk Field Air National Guard Base, Camp Douglas, Wisconsin (Dev et al, 1989), a 500 cubic foot volume of sandy soil was heated to a temperature range of 150° to 160°C. Analysis of numerous soil samples indicated a significant removal of volatile and semivolatile contaminants. The results of that field test warranted further scaled-up demonstrations to determine the feasibility of commercial application.

Site E-3 at Kelly AFB was initially proposed as a demonstration site for the IITRI method. The site was an open evaporation pit located near the old Industrial Waste Treatment Plant (IWTP) in the southern part of Kelly AFB. Unfortunately, the site geology was found to be unsuitable for the IITRI method because of the presence of a high water table and extensive gravel beds.

In September of 1991, during the Preplanning Phase, geologic evaluations indicated that Site S-1 Kelly AFB would be suitable for a demonstration of the IITRI method. HNUS, the prime contractor, subcontracted IITRI to provide technical assistance for the Preplanning Phase and Phase I.

In September 1993, after the conclusion of the IITRI demonstration, AFCEE modified the HNUS contract to include a demonstration of the KAI technique at Site S-1 Kelly AFB as part of Phase I. In addition, the technical evaluation is to include a comparison of the two technologies.

1.5 INSTALLATION LOCATION AND HISTORY

Kelly AFB lies approximately 150 miles west of the Gulf of Mexico, in Bexar County, 7 miles southwest of the center of San Antonio. The base consists of 4,660 acres, bounded on the West by Lackland AFB and on the South by Military Drive. The eastern and northern boundaries of Kelly AFB are the Missouri-Pacific Railroad yards and US Highway 90, respectively (Figure 1-1).

Kelly AFB was founded in 1917 as the first military air base in Texas. Since 1954, Kelly AFB has been involved in logistics and aircraft maintenance. The primary mission of Kelly AFB is to support the San Antonio Air Logistics Center (SA-ALC) of the Air Force Materiel Command. SA-ALC is the system support manager for the Military Airlift Command's C-5 Galaxy jet transport fleet. In addition, SA-ALC is responsible for depot maintenance for the Strategic Air Command's B-52 bomber fleet. SA-ALC also manages more than half of the Air Force engine inventory. SA-ALC manages the fuels, oil, and petroleum program for the Air Force, including liquid oxygen, nitrogen, and special fuels. Kelly AFB also acts as host to approximately 56 tenant organizations representing the USAF, the US Army, DOD, and other government agencies.

1.6 THE EPA SITE PROGRAM

EPA established the Superfund Innovative Technology Evaluation (SITE) Program to expedite the development and evaluation of innovative remedial technologies. The agency supported this project by providing analytical laboratory services for the analysis of pre-test and post-test soil samples.

2.0 IITRI DEMONSTRATION

2.1 BACKGROUND

This section presents a brief description and chronology of the IITRI pilot-scale demonstration. Results of the IITRI demonstration are presented in Section 4 (Geology and Hydrogeology), Section 5 (Radio Frequency Soil Heating), Section 6 (Soil Vapor Extraction and Treatment), Section 7 (Soil and Vapor Chemical Data), and applicable Appendices.

2.2 PREPLANNING

Due to the innovative nature of RFH technology an extensive Preplanning Phase was required for the IITRI demonstration. IITRI prepared technical reports for review by USAF and HNUS project personnel. A decision to proceed to Phase I was made based on the Preplanning Phase effort.

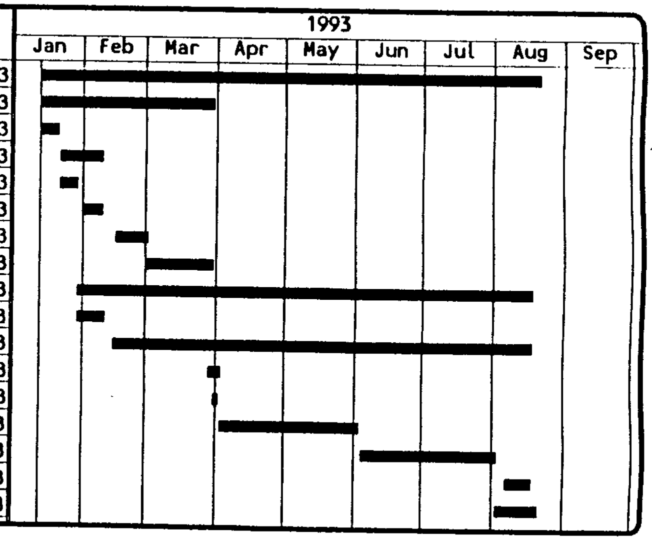
IITRI performed a Soil Treatability Study and prepared Demonstration Test and Detailed System Design Plans during the Preplanning Phase of the project. The Soil Treatability Study was performed to measure the dielectric properties of site soils in order to predict heating and power requirements and contaminant removal rates. The Demonstration Test Plan (or Work Plan) included project goals and objectives, schedule, technique-specific health and safety requirements, data collection recommendations, and results predictions. The Detailed System Design presented regulatory issues, hardware details, operational criteria, and manpower requirements. These reports were included as appendices in the Preplanning Phase technical report (HNUS, November 1993).

2.3 PHASE I DEMONSTRATION

The effort was divided into design and planning, mobilization, site preparation (including system installation), operations, and demobilization. See Figure 2-1 for a schedule of field activities. IITRI's efforts for the demonstration consisted of the design, construction, and operation of the RFH system. IITRI reviewed the HNUS Work, Health and Safety, and Sampling and Analysis Plans (HNUS, May 1993) and coordinated all design activities and operational procedures for system integration with HNUS. HNUS efforts consisted of site preparation, the design, construction, and operation of the ejector and VT system, health and safety monitoring, and site management. In addition, HNUS supported IITRI during the RFH system set-up. Routine OSHA (health and safety) working procedures for hazardous wastes were followed as dictated in the site-specific Health and Safety Plan (HNUS, March 1993).

Figure 2.1 - IITRI RFH Demonstration

Task Name	Duration	Start	End
RF HEATING Phase I - IITRI	220.00 d	Jan/13/93	Aug/21/93
SITE PREPARATION AND SYSTEM SET-UP	78.00 d	Jan/13/93	Mar/31/93
GENERAL CIVIL CONSTRUCTION	9.00 d	Jan/13/93	Jan/21/93
DRILLING	20.00 d	Jan/22/93	Feb/10/93
DEWATERING SYSTEM INSTALLATION	9.00 d	Jan/22/93	Jan/30/93
SOIL SAMPLING AND ELECTRODE INSTALLATION	10.00 d	Feb/01/93	Feb/10/93
RF SYSTEM SET-UP	15.00 d	Feb/16/93	Mar/02/93
SVE SYSTEM SET-UP	31.00 d	Mar/01/93	Mar/31/93
SYSTEM TESTING AND OPERATION	200.00 d	Jan/30/93	Aug/18/93
DEWATER TESTING	13.00 d	Jan/30/93	Feb/11/93
DEWATERING	184.00 d	Feb/15/93	Aug/18/93
SVE TESTING	6.00 d	Mar/29/93	Apr/03/93
RF TESTING	3.00 d	Mar/31/93	Apr/02/93
HEATING	61.00 d	Apr/03/93	Jun/03/93
COOLDOWN	61.00 d	Jun/04/93	Aug/03/93
POST SAMPLING & WELL ABANDONMENT	12.00 d	Aug/07/93	Aug/18/93
DEMOBILIZATION	19.00 d	Aug/03/93	Aug/21/93



2.3.1 Design and Planning

Due to changes in project scope a downsizing of the RFH design as envisioned during the Preplanning Phase was required and performed by IITRI (see Appendix A.1). IITRI also specified the procedure for the installation of the electrode wells. HNUS designed the ejector assembly used to provide SVE vacuum, the VT system, and the dewatering system (see Appendices A.8 and D).

2.3.2 Mobilization

IITRI efforts consisted of procurement, fabrication, and site delivery of the RFH system and the vapor manifold and barrier components for the SVE system. HNUS coordinated the procurement, fabrication, and delivery of the ejector assembly used to provide SVE vacuum and the VT system. HNUS also coordinated the procurement and delivery of all rental and disposable materials.

2.3.3 Site Preparation

Site preparation tasks performed by HNUS included:

- Civil construction (i.e., fencing, grading, office set-up, project sign, storage bin placement, personnel decontamination station, and transformer set-up),
- Site and safety management,
- Pre-demonstration soil sampling and installation of in-ground system components (see Appendix C).
- Dewatering system installation and operation (Appendix A.8), and
- Ejector and vapor treatment (VT) component (i.e., diesel air compressor, carbon steel transfer pipe and flare) set-up, testing, and operation (Appendices A.6 and D).

The flare was moved to the site, set up, modified, and tested by the manufacturer. IITRI constructed the vapor manifold and barrier, the RF shield, and RFH system with HNUS support.

Contaminated groundwater removed by dewatering was temporarily stored on site in a 21,000 gallon "frac tank" and regularly transferred to a 6000 gallon tanker truck for transport to the Kelly AFB EPCF for treatment and discharge (see Appendix A.8). All soil cuttings not placed over the heated zone were drummed and transported to the Kelly AFB Drum Yard for disposal (see Appendix C). See Figure 2-2 for site layout.

2.3.4 System Operation

System operation tasks consisted of SVE operation (see Appendix A.6), RFH testing and operation (see Appendix A.1), dewatering (see Appendix A.8), vapor sampling (see Section 7), tracer test RF shutdown, and cooldown (see Appendix A.1). IITRI and HNUS teamed for the operation of the RFH/SVE system. Using the "buddy system" for safety, the system was attended by two workers at all times during heating. IITRI personnel operated the RFH system and the in-ground portion of the SVE system. HNUS personnel operated the above ground portion of the SVE (including vapor sampling), the VT and the dewatering systems, and coordinated all fuel deliveries.

2.3.5 Demobilization

Demobilization of the RFH system began with RFH system shutdown. The RFH system exterior components (except the shield) were dismantled and packed for transport. The IITRI RF trailers remained on site during cooldown because one housed the temperature measurement system. These trailers were later transported to the location of the next IITRI field effort, Sandia National Laboratory. By the end of the IITRI demonstration, the USAF had modified Phase I to incorporate a demonstration of the KAI RFH technique. Therefore, demobilization did not include restoration of the site to pre-demonstration conditions. Miscellaneous support facilities like the office, signs, fence, electric distribution system, the ejector assembly, and VT system were left in place for the KAI demonstration.

HNUS began complete disassembly and demobilization with the shutdown of the SVE and VT systems at the end of the cooldown period. The VT diesel air compressor and fuel tanks were removed from the site. The RF shield and components of the dewatering system were disassembled, decontaminated, and turned over to base Civil Engineering. The vapor manifold was disassembled, decontaminated, and sold as scrap aluminum. The vapor barrier was rolled up, cut in half, and drummed for delivery to the Kelly AFB Drum Yard for disposal.

Soil boring and well abandonment tasks began next. Soil boring for post-demonstration soil sampling was performed first, followed by electrode, temperature measurement, and tracer well abandonment. The ground electrodes were decontaminated and sold as scrap aluminum. The excitor electrodes had melted in place and were removed by over reaming. Cutting and debris from the excitor electrode borings were drummed and delivered to the Kelly AFB Drum Yard for disposal.

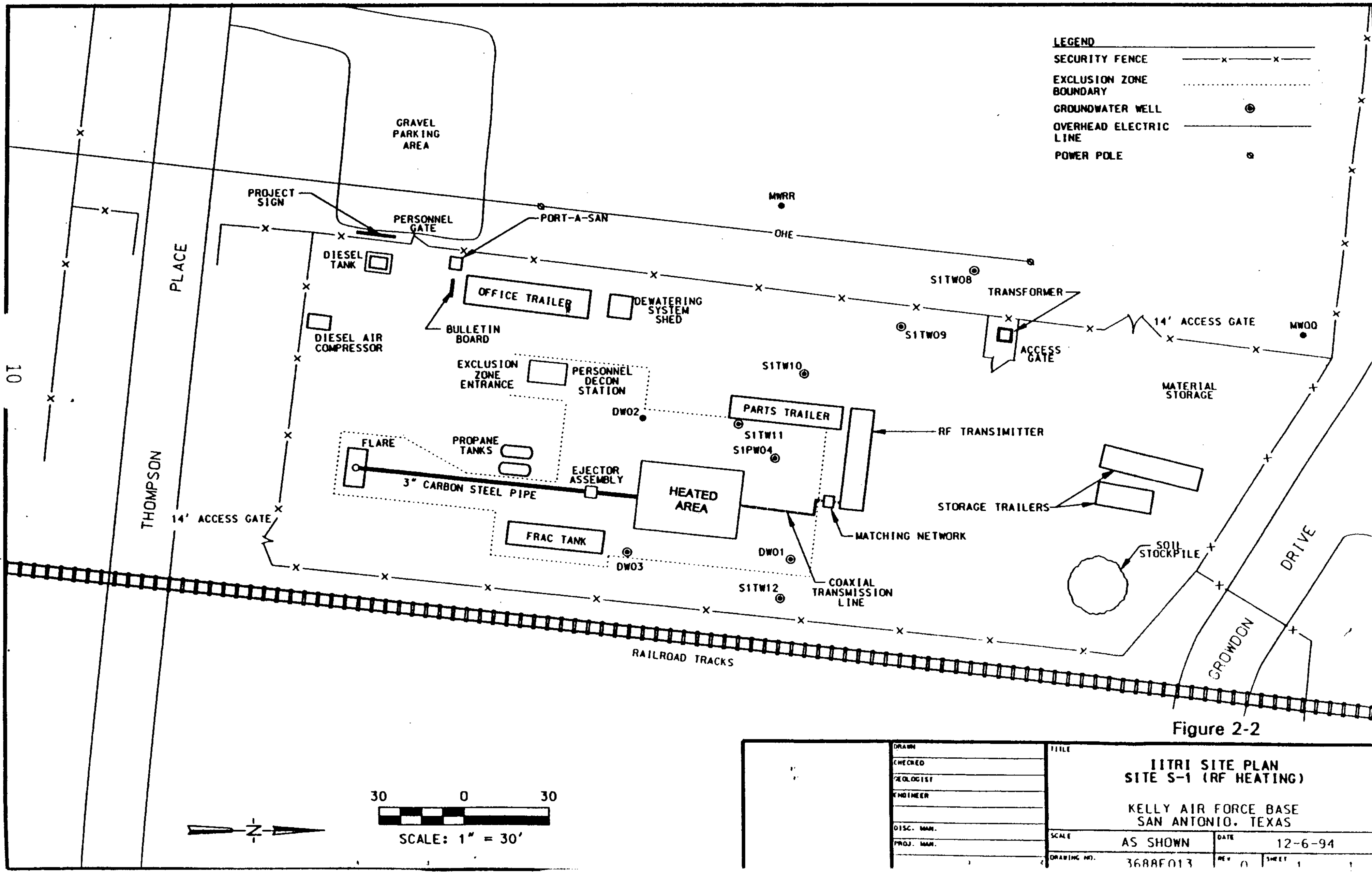

LEGEND
SECURITY FENCE
EXCLUSION ZONE BOUNDARY
GROUNDWATER WELL
OVERHEAD ELECTRIC LINE
POWER POLE
GRAVEL PARKING AREA
PROJECT SIGN
PERSONNEL GATE
PORT-A-SAN
MWRR
OHE
DIESEL TANK
OFFICE TRAILER
DEWATERING SYSTEM SHED
BULLETIN BOARD
DIESEL AIR COMPRESSOR
EXCLUSION ZONE ENTRANCE
PERSONNEL DECON STATION
S1TW08
S1TW09
S1TW10
TRANSFORMER
ACCESS GATE
14' ACCESS GATE
MW00
MATERIAL STORAGE
DW02
PARTS TRAILER
S1TW11
S1PW04
RF TRANSIMITTER
FLARE
PROPANE TANKS
3" CARBON STEEL PIPE
EJECTOR ASSEMBLY
HEATED AREA
STORAGE TRAILERS
FRAC TANK
DW03
DW01
MATCHING NETWORK
S1TW12
COAXIAL TRANSMISSION LINE
SOIL STOCKPILE
THOMPSON
PLACE
14' ACCESS GATE
RAILROAD TRACKS
GROWDON
DRIVE
30 0 30
SCALE: 1" = 30'
N
DRAWN
CHECKED
GEOLOGIST
ENGINEER
DISC. MAN.
PROJ. MAN.
TITLE
IITRI SITE PLAN
SITE S-1 (RF HEATING)
KELLY AIR FORCE BASE
SAN ANTONIO, TEXAS
SCALE
AS SHOWN
DATE
12-6-94
DRAWING NO.
368BF013
REV
0
SHEET
1

Figure 2-2

The dewatering system disassembly began with the completion of post-demonstration soil sampling and well abandonment. The dewatering ejectors and head controls were decontaminated and stored with the control panel. PPE, dewatering hose, and miscellaneous plastic, wire, wood, and pipe contaminated during operations were drummed and delivered to the Kelly AFB Drum Yard for disposal. Small quantities of various uncontaminated disposables (i.e., scrap metal, wood, pipe, and wire) were placed in a Kelly AFB trash receptacle for disposal.

Final demobilization included return of rented equipment. The portable toilet, one of two portable storage bins, cellular phones, and health and safety equipment (i.e., OVA, LEL, calibration gas tanks, stretcher, first aid kit, and personnel respirators with spare oxygen tanks) were returned to their respective vendors.

3.0 KAI DEMONSTRATION

3.1 BACKGROUND

This section presents a brief description and chronology of the KAI pilot demonstration. Results of the KAI demonstration are presented in Section 4 (Geology and Hydrogeology), Section 5 (Radio Frequency Soil Heating), Section 6 (Soil Vapor Extraction and Treatment), Section 7 (Chemical and Physical Data), and applicable Appendices.

Due to the experience and knowledge gained during the Preplanning Phase and the IITRI demonstration, detailed design and demonstration plans were not required for the KAI demonstration.

3.2 PHASE I DEMONSTRATION

The effort was divided into design and planning, mobilization, site preparation (including system install), operations, and demobilization. See Figure 3-1 for a schedule of field activities. KAI's efforts for the demonstration consisted of the design, construction, and operation of the RFH system. HNUS efforts consisted of site preparation, design, construction, and operation of the SVE and VT systems, and providing the Site Manager (SM) and Site Safety Officer (SSO). In addition, Halliburton NUS supported KAI during the RFH system set-up. Routine OSHA (health and safety) working procedures for hazardous wastes were followed as dictated in the site-specific Health and Safety Plan (HNUS, March 1993).

3.2.1 Design and Planning

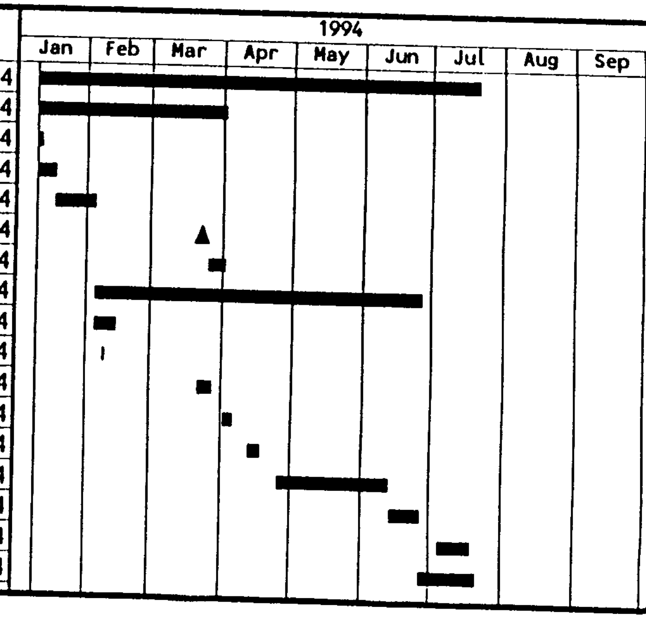
KAI reviewed the HNUS Work, Health and Safety, and Sampling and Analysis Plans, and coordinated all design activities and operational procedures for system integration with HNUS. KAI designed the RFH system. HNUS designed the SVE system to incorporate existing ejector and VT components.

3.2.2 Mobilization

KAI's tasks included the procurement, fabrication, and site delivery of the RFH system. HNUS tasks included the procurement, fabrication, and site delivery of the SVE system and the procurement and delivery of all rental and disposable materials.

Figure 3.1 - KAI RFH Demonstration

Task Name	Duration	Start	End
RF HEATING Phase I - KAI	193.00 d	Jan/10/94	Jul/21/94
SITE PREPARATION	83.00 d	Jan/10/94	Apr/02/94
GENERAL CIVIL CONSTRUCTION	3.00 d	Jan/10/94	Jan/12/94
DRILLING (Sampling & Partial Set-Up)	9.00 d	Jan/10/94	Jan/18/94
SVE SYSTEM SET-UP	19.00 d	Jan/18/94	Feb/05/94
ANTENNA SLEEVE DELIVERY	0.00 d	Mar/23/94	Mar/23/94
RF SYSTEM SET-UP	8.00 d	Mar/26/94	Apr/02/94
SYSTEM TESTING & OPERATION	143.00 d	Feb/05/94	Jun/27/94
SVE & VT TESTING #1	10.00 d	Feb/05/94	Feb/14/94
EPA/SITE SVE TESTING	1.00 d	Feb/09/94	Feb/09/94
SVE TESTING #2	7.00 d	Mar/22/94	Mar/28/94
RF TESTING	5.00 d	Apr/02/94	Apr/06/94
SVE TESTING #3 (Optional)	6.00 d	Apr/13/94	Apr/18/94
HEATING	49.00 d	Apr/26/94	Jun/13/94
COOLDOWN	14.00 d	Jun/14/94	Jun/27/94
POST SAMPLING & WELL ABANDONMENT	15.00 d	Jul/05/94	Jul/19/94
DEMOBILIZATION	25.00 d	Jun/27/94	Jul/21/94



3.2.3 Site Preparation

Site preparation tasks performed by HNUS included civil construction (i.e., grading and transformer set-up), site and safety management, pre-demonstration soil sampling and well installation (i.e., antenna, temperature, vapor extraction, and field measurement wells) (see Appendix C), vapor manifold and barrier construction (see Section 6 and Appendix B.3), and SVE and VT component testing (see Appendix B.4). KAI set up the RFH system with HNUS support. All drill cuttings were drummed and transported to the Kelly AFB Drum Lot for disposal. See Figure 3-2 for site layout details.

An initial SVE/VT test was performed to define operational procedures. During the initial test HNUS personnel assisted EPA/SITE in the performance of a series of SVE tests utilizing a computerized transducer system. A second test of the SVE/VT systems was performed to fine-tune the procedures, but due to a clogged ejector results were meaningless and a third SVE/VT test was required.

3.2.4 System Operation

System operation tasks consisted of the initial SVE testing and operation (Appendix B.4), RFH testing and operation (Appendix B.1), vapor sampling (Section 7), RF shutdown, and cooldown. KAI and HNUS teamed for the operation of the RFH/SVE system. Using the buddy system for safety, the system was attended by two workers during daylight hours. The site was unattended during the evening and early morning periods and on Sundays. KAI personnel operated the RFH system. HNUS personnel operated the SVE (including sampling) and VT systems and coordinated all fuel and material deliveries.

3.2.5 Demobilization

The demobilization task restored the site to pre-demonstration conditions. Demobilization of the RFH system began with RFH system shutdown. The RFH system exterior components were dismantled and packed away for transport. The RF trailer housed the soil temperature measurement system and, therefore, remained on site during cooldown.

HNUS began complete disassembly and demobilization with the shutdown of the SVE and VT systems at the end of the cooldown period. The ejector assembly and VT system were removed from the site with the associated diesel air compressor, fuel tanks, piping, and scaffolding.

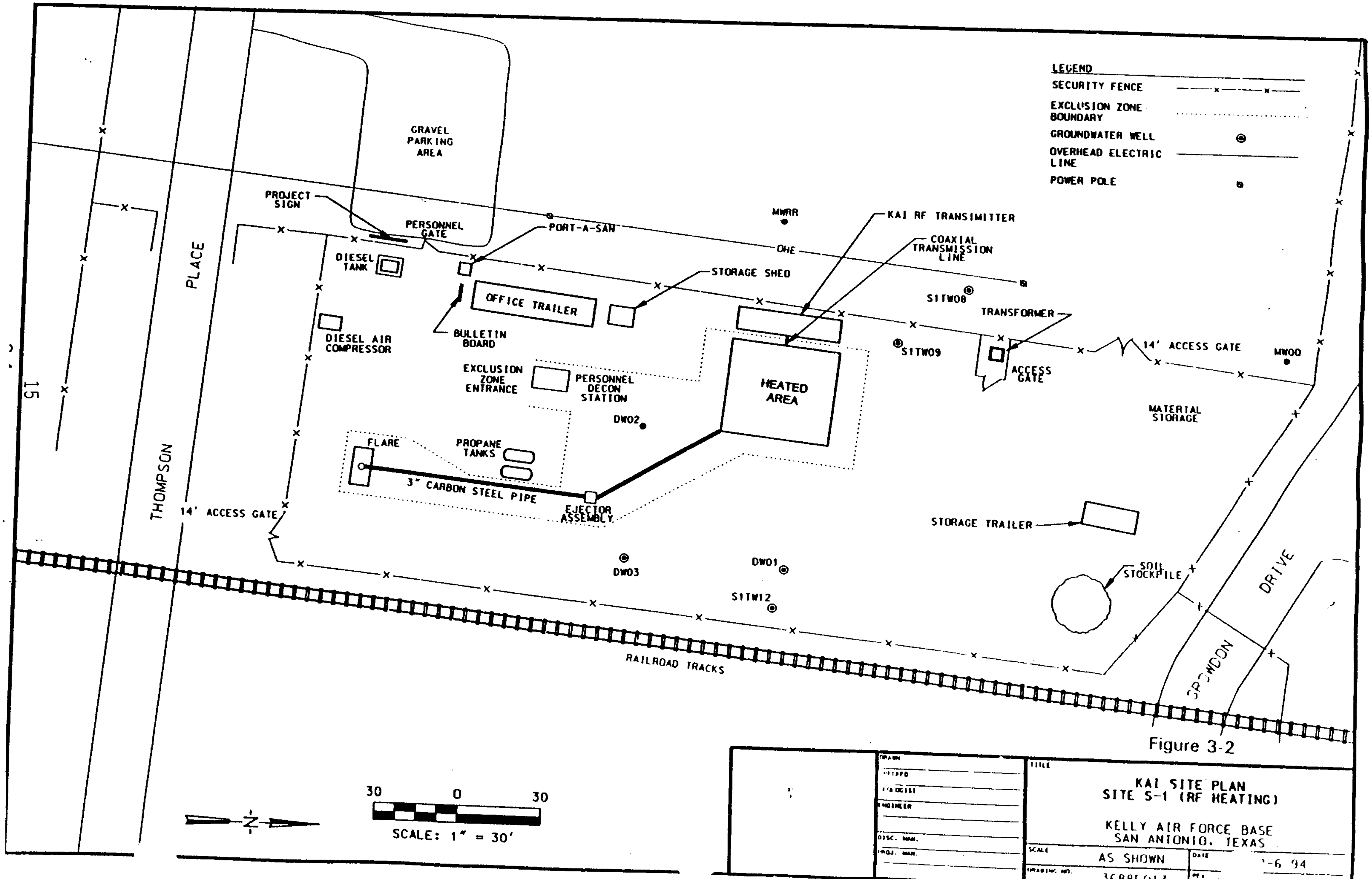

LEGEND
SECURITY FENCE
EXCLUSION ZONE BOUNDARY
GROUNDWATER WELL
OVERHEAD ELECTRIC LINE
POWER POLE
GRAVEL PARKING AREA
PROJECT SIGN
PERSONNEL GATE
PORT-A-SAN
DIESEL TANK
DIESEL AIR COMPRESSOR
OFFICE TRAILER
BULLETIN BOARD
STORAGE SHED
KAI RF TRANSIMITTER
COAXIAL TRANSMISSION LINE
OHE
MWRR
S1TW08
S1TW09
TRANSFORMER
ACCESS GATE
14' ACCESS GATE
MW00
MATERIAL STORAGE
EXCLUSION ZONE ENTRANCE
PERSONNEL DECON STATION
HEATED AREA
DW02
FLARE
PROPANE TANKS
3" CARBON STEEL PIPE
EJECTOR ASSEMBLY
14' ACCESS GATE
STORAGE TRAILER
SOIL STOCKPILE
DW03
DW01
S1TW12
RAILROAD TRACKS
THOMPSON PLACE
DRIVE
SPOWDON
N
30 0 30
SCALE: 1" = 30'
KAI SITE PLAN
SITE S-1 (RF HEATING)
KELLY AIR FORCE BASE
SAN ANTONIO, TEXAS
AS SHOWN
3688E013

Figure 3-2

The VT flare, property of Kelly AFB, was disassembled and stored on site. The vapor manifold was disassembled, decontaminated, and placed in a trash receptacle for disposal. The vapor barrier was drummed and delivered to the Kelly AFB Drum Lot for disposal.

Soil boring and well abandonment tasks began next. Soil boring for post-demonstration soil sampling was performed first, followed by antenna, extraction, and temperature and ground pressure measurement well abandonment. Drill cuttings were drummed and delivered to the Kelly AFB Drum Lot for disposal.

PPE and small quantities of miscellaneous plastic sheets, bags, wire, wood, hoses, and pipe contaminated during operations were drummed and delivered to the Kelly AFB Drum Lot for disposal. Various uncontaminated disposables (i.e., scrap metal and wood, pipe, and wire) were placed in a trash receptacle for disposal.

Final demobilization included return of rented equipment. The office, transformer, portable toilet, portable storage bin, cellular phones, and health and safety equipment (i.e., OVA, LEL, calibration gas tanks, stretcher, first aid kit, and personnel respirators with spare oxygen tanks) were returned to their respective vendors. The sign and bulletin board were dismantled and removed.

4.0 DEMONSTRATION ENVIRONMENTAL SETTING

4.1 REGIONAL SETTING

4.1.1 Geography

Kelly AFB lies in the western portion of the Gulf Coastal Plain, a gently undulating prairie with elevations ranging from 450 feet to approximately 700 feet above the National Geodetic Vertical Datum (NGVD). The plain slopes to the Southeast toward the Gulf of Mexico. Elevations at Kelly AFB vary from 730 to 620 feet above NGVD. Lower elevations lie along Leon Creek at the southern boundary of the base.

The San Antonio area lies within two distinct physiographic regions, the Edwards Plateau secondtion of the Great Plains Province and the western Gulf Coastal Plain. The southwest-northeast trending Balcones Escarpment divides the two regions. The plateau serves as a recharge area for surface waters flowing to aquifers and streams extending through the San Antonio area.

4.1.2 Geology

The region surrounding Kelly AFB is underlain by Quaternary alluvium over a thick stratigraphic sequence of Cretaceous sediments. The alluvium consists of mixtures of clay, silt, sand, and gravel. These deposits are typically 10 to 35 feet thick. The Cretaceous unit is the Navarro Group clay. The Navarro Group clay and other limestone and shale units form a thick aquitard sequence between the alluvium and the underlying Edwards Group limestone (NUS, 1991).

4.1.3 Hydrology

4.1.3.1 Surface Drainage

Surface runoff at Site S-1 drains eastward to Apache Creek, approximately 2.5 miles away. Apache Creek flows into San Pedro Creek, which in turn flows into the San Antonio River.

4.1.3.2 Groundwater

Kelly AFB lies above two groundwater aquifers. The uppermost aquifer lies within the lower strata of the Quaternary alluvium. Although this aquifer is capable of providing potable water, the quality and quantity are variable and questionable. The second aquifer is contained within the Edwards Group and is separated from the first aquifer by the Navarro Clay (HNUS, 1992). The Texas Legislature established the Edwards Aquifer Underground Water District in 1959 to provide for the systematic planning and protection of groundwater in this aquifer. The EPA designated the Edwards a sole source aquifer in 1975 (40 CFR 149).

4.2 SITE S-1

4.2.1 Topography and Drainage

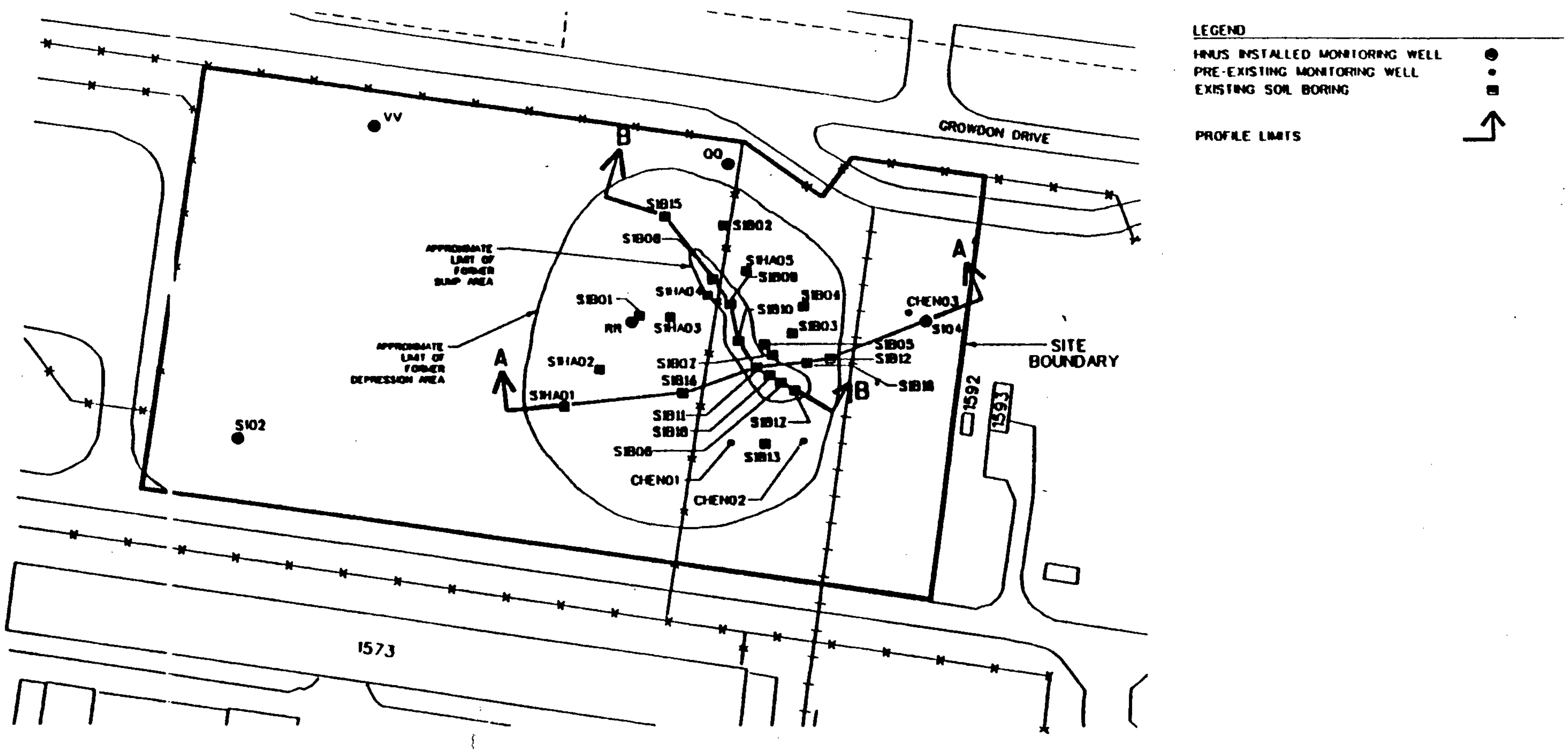
Site S-1 (See Figure 4-1) is generally flat, with surface elevations ranging from 690 to 691 feet above NGVD. Gravel covers the area over the former sump, but grass covers most of the remainder of the site. Rainfall at the site is likely to pool on the surface because of the slight topographic relief and low infiltration rates.

4.2.2 Geology

The alluvial material at Site S-1 consists of an upper layer of dark brown to black clay typically 7 feet thick overlying either a reddish brown silty clay or a clayey gravel, sand/gravel unit. The reddish brown silty clay lies in the southeast corner of the site and is usually 7 to 10 feet thick. The coarse-grained unit underlying the remainder of the site consists of subrounded to subangular limestone and chert (Figures 4-2 and 4-3).

Much of the alluvium was removed and replaced by fill material in the former depression area. The fill material is dark brown to black gravely clay with occasional zones of sand and silt covering an area approximately 150 by 300 feet. The depth ranges from 0 feet at the edge of the sump to 25 feet at its center. Large limestone and chert gravels up to 3 inches in diameter are scattered throughout much of the unit. Included in the fill material was trash, broken glass, wire, metal fragments, plastic, cans, wood fragments, and concrete rubble. Several pieces of concrete were large enough to obstruct the augers and had to be removed by a backhoe at the IITRI site.

The regional aquitard, the Navarro Group clay, lies 28 to 33 feet below the former depression area. Under Site S-1, the Navarro clay is a mottled, orange-brown to gray, stiff, plastic clay with crude laminae. A few borings have revealed silty horizons within the clay.



NOTES:

1. BASE MAP ADAPTED FROM DRAWINGS PROVIDED BY KELLY AIR FORCE BASE.
2. SOIL BORING S1B06 WAS CONVERTED TO PUMPING WELL S1PW03; SOIL BORING S1B07 WAS CONVERTED TO PUMPING WELL S1PW04. CHEN01, CHEN02, AND CHEN03 WERE USED TO OBTAIN ADDITIONAL INFORMATION ON DEPTH TO THE NAVARRO CLAY LAYER AND REMAINING BORINGS WERE USED PRIMARILY FOR ANALYTICAL PURPOSES.

GRAPHIC SCALE

0 150' 300'

HALLIBURTON NUS
Environmental Corporation

Figure 4-1

TITLE

PROFILE LOCATION MAP

SITE S-1
KELLY AIR FORCE BASE

DRAWING NO. 3688G004

DATE 10-6-92

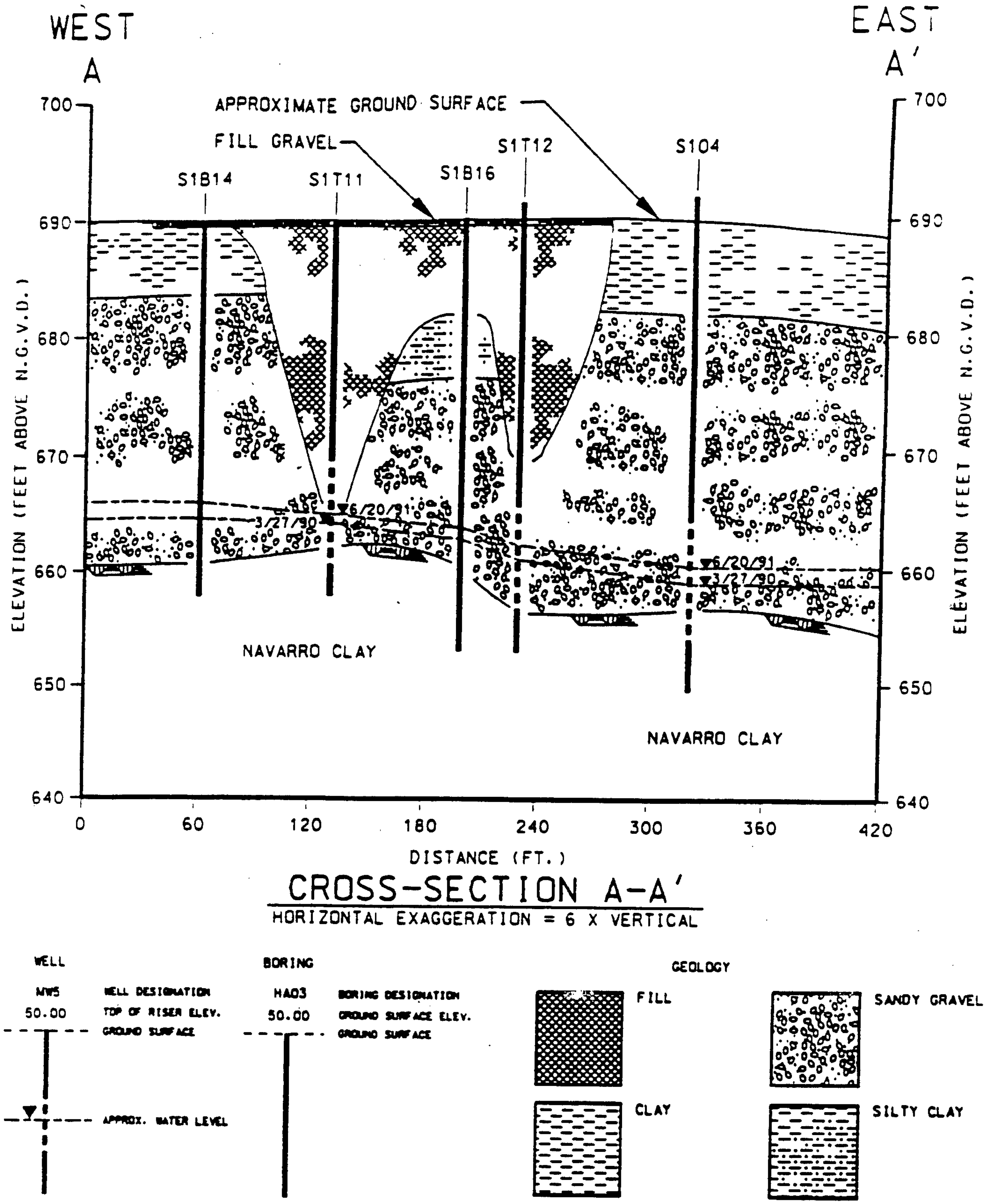


Figure 4-2

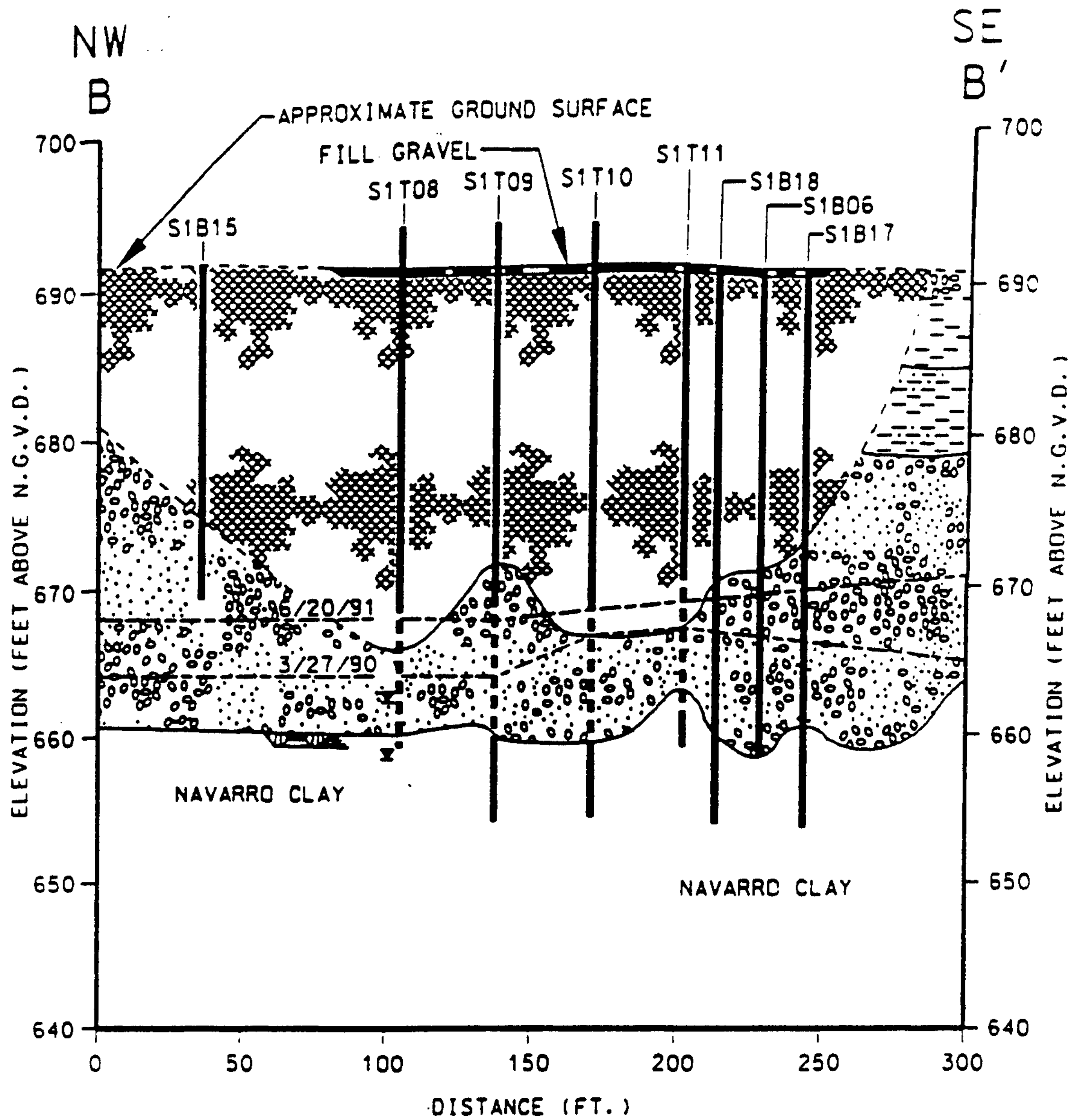
HALLIBURTON NUS
Environmental Corporation

TITLE

GEOLOGIC CROSS SECTION A-A′

SITE S-1
KELLY AIR FORCE BASE

DRAWING NO. 3688G005 DATE 10-6-92



CROSS-SECTION B–B'

HORIZONTAL EXAGGERATION = 5 X VERTICAL

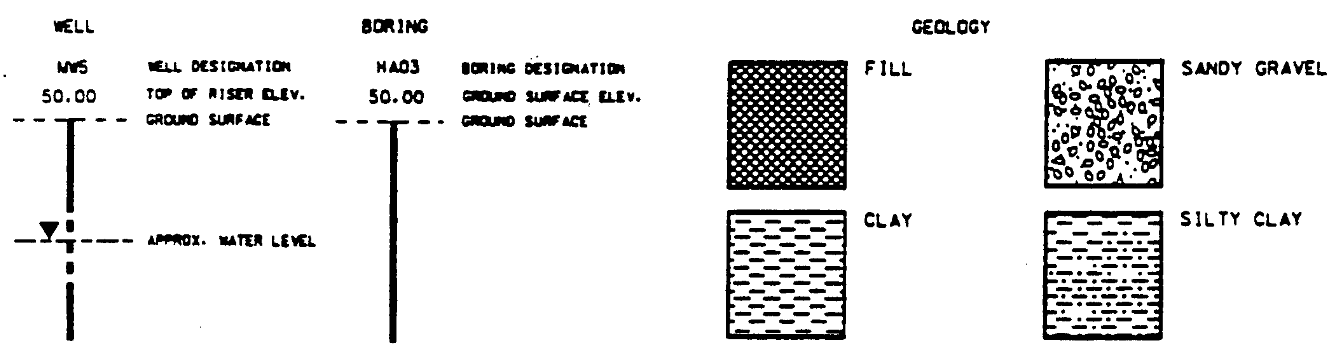


Figure 4-3

HALLIBURTON NUS
Environmental Corporation

TITLE

GEOLOGIC CROSS-SECTION B–B'

SITE S–1
KELLY AIR FORCE BASE

DRAWING NO. 213688G006

DATE 10–6–92

4.2.3 Hydrology

Aquifer Characteristics

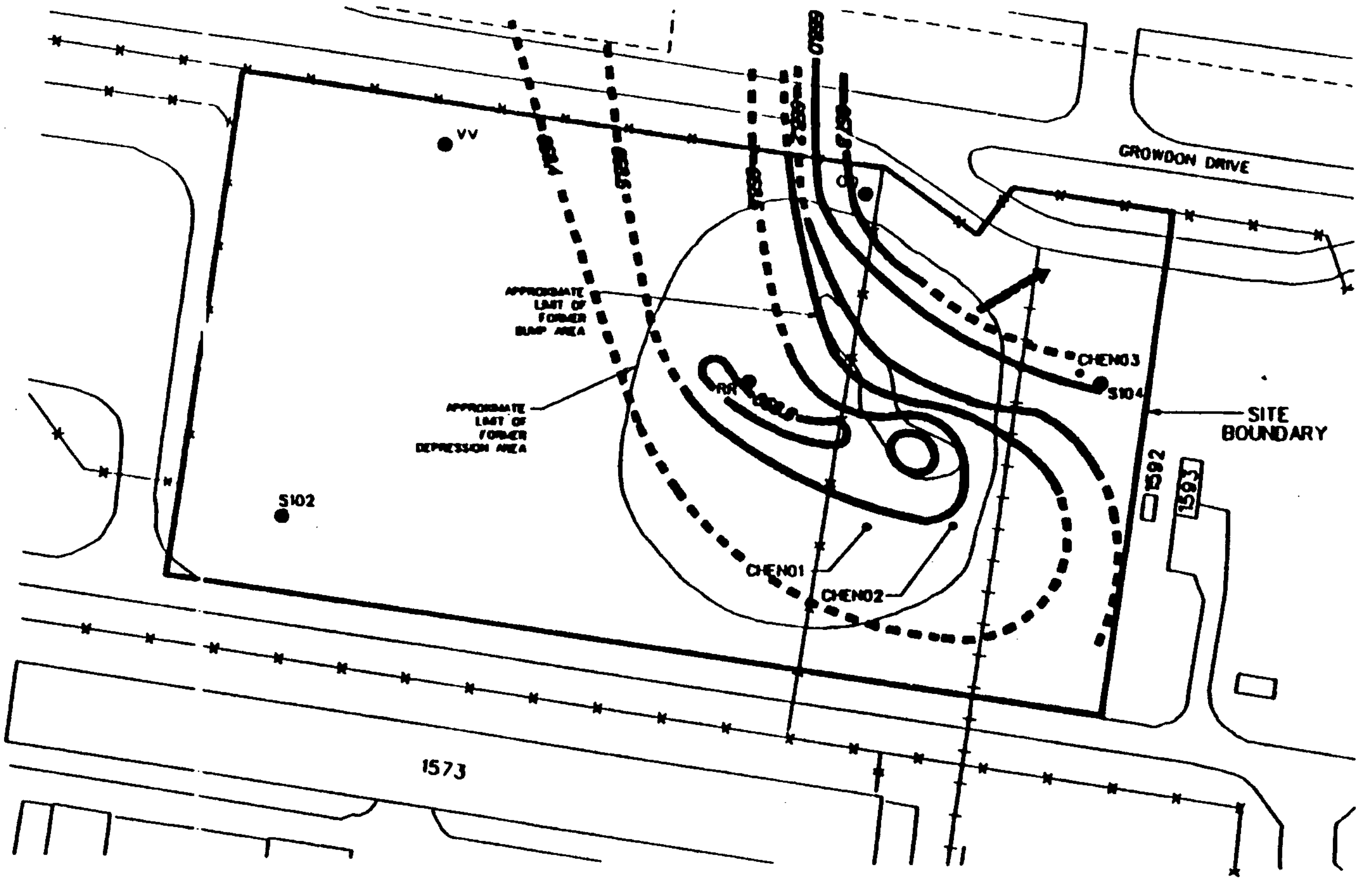
Water level measurements recorded between mid-1989 and late-1990 indicate that the direction of groundwater flow is toward the Northeast. The water table beneath the site ranged from 25 to 30 feet below the surface, with a saturated aquifer thickness of 3 to 6 feet. The maximum water level fluctuation observed in the vicinity of Site S-1 was 3.25 feet. Northeast of the sump, water level measurements made on April 30, 1992 indicated that the groundwater gradient was 0.016 ft/ft, much higher than the 0.003 feet/feet gradient found immediately downgradient of the site. A local high area in the Navarro clay in combination with a groundwater "mound" effect appears to be the cause for the steep gradient across the sump (HNUS, 1991). See Figure 4-4 for details.

Aquifer Testing

Slug tests were performed in 6 Site S-1 wells surrounding the sump area (RR, QQ, VV, S101, S102, and S104) and S1PW04 (HNUS, 1991). Although these wells lie outside the fill and sump area, they are screened across the natural gravely clay, sand/gravel unit. The calculated average hydraulic conductivity at those wells is 5.4×10^{-3} centimeter/second (1.8×10^{-4} feet/second). Data from dewatering activities during the demonstration is presented in Appendix B.8.

Aquitard Characteristics

The Navarro clay aquitard inhibits the groundwater movement both vertically and horizontally underneath the alluvium at Site S-1. The calculated mean hydraulic conductivity of 7 wells screened across the Navarro Group clay is 8.9×10^{-6} centimeter/second.



LEGEND

- HNUS INSTALLED MONITORING WELL
- PRE-EXISTING MONITORING WELL
- GROUNDWATER CONTOUR[1] (DASHED WHERE APPROX.) —100—
- GROUNDWATER FLOW DIRECTION

[1] ELEVATION IN FEET ABOVE NATIONAL GEODETIC VERTICAL DATUM

NOTES:

1. BASE MAP ADAPTED FROM DRAWINGS PROVIDED BY KELLY AIR FORCE BASE.
2. SOIL BORING S1806 WAS CONVERTED TO PUMPING WELL S1PW03; SOIL BORING S1807 WAS CONVERTED TO PUMPING WELL S1PW04; CHEN01, CHEN02, AND CHEN03 WERE USED TO OBTAIN ADDITIONAL INFORMATION ON DEPTH TO THE NAVARRO CLAY LAYER AND REMAINING BORINGS WERE USED PRIMARILY FOR ANALYTICAL PURPOSES.

GRAPHIC SCALE: 0 — 150' — 300'

Figure 4-4

HALLIBURTON NUS *Environmental Corporation*

TITLE

GROUNDWATER ELEVATION CONTOUR MAP
APRIL 30, 1992

SITE S-1
KELLY AIR FORCE BASE

DRAWING NO. 3688G004 | DATE 10-6-92

5.0 RADIO FREQUENCY SOIL HEATING

jor electrical processes employed in the RF soil decontamination demonstrations at Site S-1 :ribed below. The text begins with a brief discussion of the electrical phenomena involved, ıs some common electrical heating techniques, and concludes with more detailed ions of the IIT and KAI techniques. Additional details on both techniques are provided in ices A.1 and B.1. Some of the discussion below is very basic, presented for readers who familiar with electrical phenomena. Other readers may wish to move directly to Section 7 lts of the two demonstrations at Kelly AFB.

GENERAL

:hnologies, RFH and SVE, are required for RF soil decontamination. RFH increases the vapor ı of contaminants and soil moisture, increasing their rate of evaporation. SVE removes ınant and water vapors for treatment, assuring that vapors do not pose health or nental risks above ground level.

soils has evolved from techniques that were developed to increase the yield of oil wells. ators at IIT and elsewhere have demonstrated the feasibility of heating low-yielding oil s by application of RF energy. More recently, IIT, KAI, and others have modified these ues for near-surface use.

becoming widely used as an alternative to more expensive soil treatment technologies such ıeration. It is most effective for highly volatile soil contaminants such as gasoline. Many latile contaminants may be removed if the soil is heated, and soil heating can extend the of SVE into very cold climates. Recent SVE innovations include the use of steam injection ar heating of injected air or water. SVE and the system used in these demonstrations are ıed in more detail in Section 6.

ar-surface soils at Site S-1 were heated to temperatures exceeding 100 degrees Celsius by tion of RF energy. Heating vaporized many volatile site contaminants because the soil ature exceeded their boiling points. Heating increased the vapor pressure of all ıinants, so heavier compounds that boil at higher temperatures vaporized more quickly.

:al literature usually discusses the transfer of energy to a dielectric in terms of the loss t, δ. Materials that heat easily are described as "lossy". Soil impedance is a complex n consisting of a real component that describes the degree to which the soil is lossy and a : component that describes the soil's ability to store energy. The loss tangent, δ, is the ratio lossy component to the reactive component. These discussions may lead to confusion e:

- Dielectric "loss" or "lossy" have negative connotations for many people, but "lossy" soils are the easiest to heat with RF energy.
- Complex discussions of impedance may intimidate readers. They may feel that complex concepts must reflect complex operational problems.

ils are suitable for RFH (δ is sufficiently large). Sand, gravel, or rock (low δ) require much reful consideration. In most applications, the primary concern is to the operator, who must n operating frequency, design his applicator for site conditions, and adapt to changes in δ become dry. Recent articles on RFH of soils illustrate the difficulty that radio engineers ice explaining this concept to a more general audience. Authors often speak of depositing, ng, or transferring energy. For simplicity, this report describes the process as dielectrics ng" energy from an electric field.

Resistance, Inductance, and Capacitance

ice

ductors offer some resistance to the flow of electrical currents at temperatures above : zero. The resistance of power distribution lines results in some waste of energy, while the ; in electronic circuits are critical to the circuits' operation. Ohm's Law describes the ship between voltage, current, and resistance:

$$E = IR$$

E = the voltage difference, or potential, across a resistor (volts)

I = the current flowing through the resistor (amperes)

R = the resistance (ohms)

Inductance

The henry is the unit of measure of inductance. Inductance is associated with the creation of a magnetic field around a conductor carrying an electric current. Coils, such as those in transformers, are the most common inductors, but all current-carrying devices exhibit inductance. As discussed below, the inductance inherent in RF application systems must be closely monitored. The application of RF energy to soil does not rely on inductive phenomena, however.

Capacitance

The simplest capacitor is two parallel plates separated by an air gap. Capacitors may have other shapes, may consist of multiple, interleaved plates, and the plates may be separated by a wide variety of dielectric materials. Capacitors are used to block DC currents, adjust the frequency of tuned RF circuits, and reduce or offset inductance in circuits. The farad is the unit of capacitance.

Inductive and Capacitive Effects on Alternating Currents

The voltage in household AC circuits rises sinusoidally from zero to a peak of 110 volts, falls to minus 110 volts, and returns to zero at a frequency of 60 Hz. RF sources used for soil heating supply a similar current at much higher voltages and at frequencies of several megahertz. If the inductance and capacitance of the circuits receiving such currents are negligible, the voltage and current rise and fall synchronously and are said to be "in phase". Strongly inductive or capacitive circuits change the voltage/current phase relationship.

In inductive devices like transformers and motors, the voltage rises before the current. The current is said to "lag" in such devices. The current "leads" the voltage in capacitive devices. The voltage and current are "out of phase" in both cases, and the power delivered to these circuits is not a simple function of voltage and current. Power is also a function of the phase difference between voltage and current. Peak power must be less than the product of voltage and current because voltage and current do not reach their peak values simultaneously.

Inductive and capacitive effects cause potential, but correctable, losses of efficiency. For example, the electrical efficiency of an installation containing large motors (an inductive load) may be improved by placing capacitors on the incoming power line. The rows of electrodes in the IIT electrode array behave like the plates of a large capacitor with soil acting as a dielectric. Power is supplied to the array through an adjustable matching network to minimize undesirable capacitive effects.

Applicator systems like IIT's electrode arrays or KAI's antennae exhibit a complex combination of resistance, inductance, and capacitance called impedance. RF sources are designed to deliver power into a prescribed impedance. At radio frequencies, a large portion of the power applied to the soil may be reflected back along the distribution line to the RF source unless the impedance of the applicator matches the prescribed impedance of the source. The impedance match is never perfect in practice because:

- An ideal coaxial line connecting the source to the applicator should, in theory, carry RF energy any desired distance with no losses. Actual coaxial systems and other components exhibit slight impedance irregularities that preclude a perfect impedance match.

- The properties of the soil being treated change throughout the heating process. The progressive soil drying changes its dielectric properties and, consequently, its impedance.

  Excessive reflected power results in inefficient heating and can cause serious damage to the RF source. The IIT and KAI systems monitor the efficiency of power delivery and adjust automatically to normal impedance changes. Larger changes, like those that might occur if a component fails, activate alarms to alert operators or turn off power to the system.

5.3 ELECTRICAL HEATING TECHNIQUES

5.3.1 Ohmic Heating

Three electrical heating techniques are widely used in industry and by individuals. Ohmic, or resistive, heating is the most common, and a cooking eye on an electric kitchen range is a very familiar example. Ohmic heating may be used to heat soils by applying a high voltage, 60-Hertz current to electrodes driven into the soil. The simplicity of the technique makes it attractive, and it may be useful for small, shallow contaminated zones. There are two drawbacks, however. Large quantities of soil cannot be treated without the use of very high, and therefore dangerous, voltages and currents. Also, this technique relies on soil moisture to provide a conductive path through the soil. The moisture is removed when soil temperatures reach about 100 degrees Celsius, breaking the conductive path and stopping the heating process.

DOE investigators at Pacific Northwest Laboratories and the DOE Savannah River Site have developed and demonstrated a novel improvement on this technique (Gauglitz, 1994). They applied six-phase AC to six electrodes equally spaced on 15-foot radii around a central SVE well. This approach creates constantly changing voltage differences between pairs or groups of pairs of electrodes. The observed heating pattern was sufficiently uniform to warrant further testing. Even if water must be added to site soils periodically, the technique may prove useful for removal of very volatile compounds.

5.3.2 Inductive Heating

Inductive heating employs an electrical current applied through a coil to produce an intense magnetic field inside the coil. The field acts only on magnetic materials and has little effect on dielectrics. This technique is widely used to produce metals of extremely high purity and to heat metal bars for annealing or forging. The heated volumes are typically quite small, offering little utility for soil heating.

5.3.3 Dielectric Heating

Dielectric heating employs a high-frequency alternating electric field to heat the desired volume. Polar molecules such as water are caused to vibrate at the applied RF frequency, and the resulting mechanical energy is released as heat. Diathermy, a medical technique that is several decades old, is used to heat small portions of the human body by stimulating the body's fluids. The microwave oven is the most popular current application of dielectric heating; food is heated rapidly and efficiently when ultra-high frequency energy agitates water molecules in the food. Dielectric soil heating and microwave food preparation are also similar in that metal objects must not be placed within the heated zone. Such objects absorb RF energy very strongly, resulting in extremely high temperatures near the objects and possible damage to the RF source.

The RF soil decontamination demonstrations discussed in this report are examples of dielectric soil heating. In the IIT demonstration, RF energy was applied to rows of electrodes in soils at Site S-1, where the soils, water, and other materials between the electrode rows behaved like the dielectric medium in a capacitor. KAI applied RF energy with an antenna-like device inverted and lowered several feet into a well.

RF soil decontamination proceeds in three steps. First, soil moisture and contaminants are heated by the application of RF energy, vaporizing both the moisture and contaminants. The vapors are then removed by vacuum extraction techniques similar to those used in commercial SVE and soil organic vapor (SOV) sampling processes. Finally, the extracted heated vapors may be treated, destroyed, or recycled by a variety of commercially available processes.

Successful application of RFH of soil requires consideration of two complicating factors. First, the electrical properties of the soil may vary greatly as treatment proceeds. These changes require careful monitoring and tuning of the RF source to optimize the transfer of electrical energy to the soil. Second, soil moisture and contamination may vary greatly within the treated volume. These variations may produce short-term changes in the composition of the extracted vapor stream. The vapor treatment system must be designed to accommodate such changes and monitored to assure that vapors are properly contained.

5.4 THE PROPAGATION OF RF ENERGY

5.4.1 RF Propagation in Free Space

RF energy is usually represented as perpendicular electric and magnetic vectors, as shown in Figure 5-1. The electric and magnetic field intensities vary sinusoidally at a frequency determined by the RF source. The distance along the path of propagation required to complete each cycle is called the wavelength. Frequency and wavelength are related by the expression:

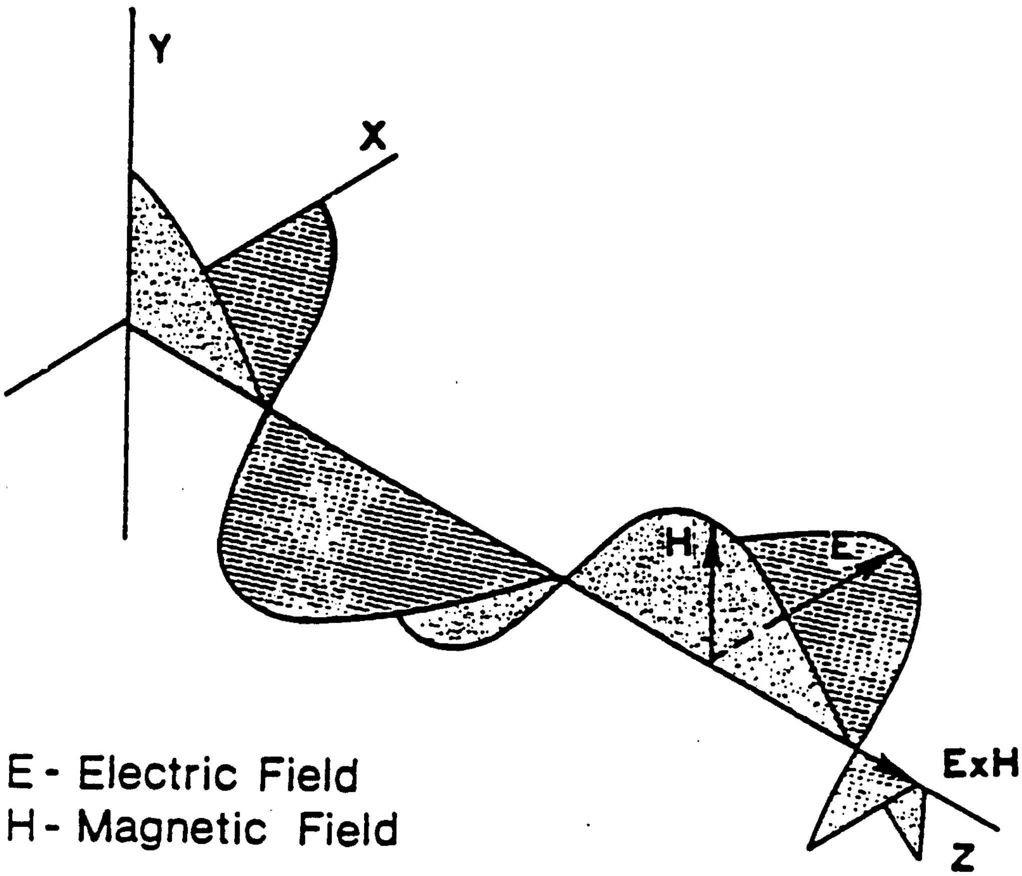
$$\lambda f = c$$

where

- λ = the wavelength of the radiation in free space in meters
- f = the frequency of the radiation in Hertz
- c = the speed of light, approximately 300,000,000 (3×10^8) meters per second

A frequency of 6.78 megahertz, the frequency IIT used for the demonstration at Site S-1, corresponds to a wavelength of 44.2 meters in free space. The relationship of radio frequency radiation to other forms of electromagnetic radiation is shown in Figure 5-2.

The use of RF energy described above must not interfere with communications, radar, or other RF applications. IIT and KAI operate their systems at frequencies in the Industrial, Scientific, and Medical (ISM) frequency bands established by The Federal Communications Commission (FCC). Unlicensed users may operate RF equipment within these frequency bands at very high power



E - Electric Field
H - Magnetic Field

(Source: AFOSH Standard 161-9)

Figure 5-1

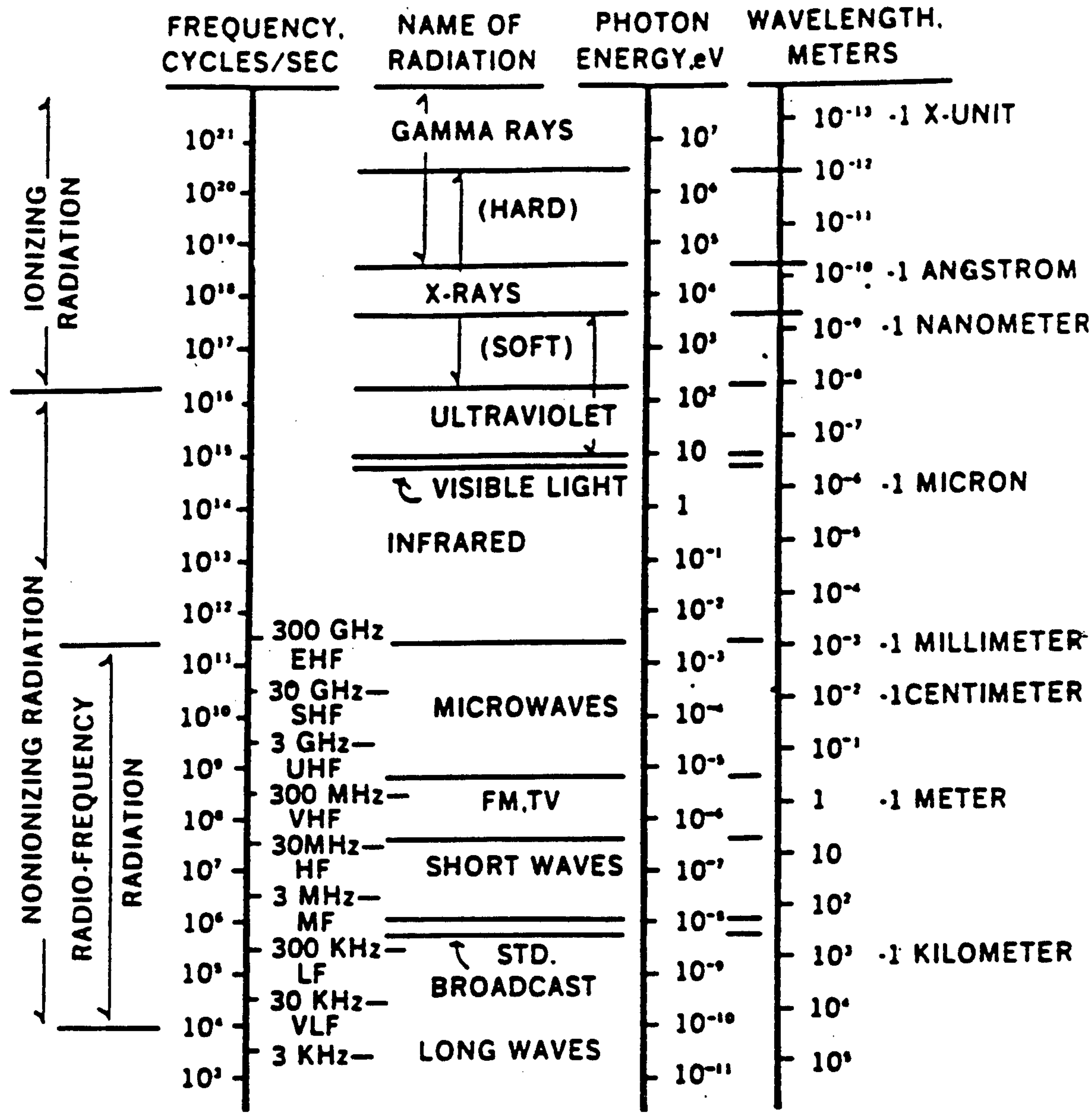
HALLIBURTON NUS
Environmental Corporation

TITLE

PROPERTIES OF ELECTROMAGNETIC WAVES

DRAWING NO.

DATE



(Source: AFOSH Standard 161-9)

Figure 5-2

HALLIBURTON NUS *Environmental Corporation*

TITLE

THE ELECTROMAGNETIC SPECTRUM

DRAWING NO. | DATE

levels and with somewhat broader frequency bandwidth (range of frequencies around the design frequency) than allowed on most communication frequencies. No FCC permit is required, but operation must be coordinated with base communications personnel.

5.4.2 RF Propagation in Dielectrics

Dielectric materials contain polar molecules, or dipoles, which vibrate at the frequency of the applied electric field. The amplitude of the electric field decreases with distance as RF energy is converted to mechanical energy, then lost as heat. The magnetic field decreases in proportion to the reduction of the electric field. The behavior of the magnetic field is relatively unimportant to an understanding of the heating process unless metallic objects lie in the heated zone. Such objects behave like a spoon inadvertently heated in a microwave oven and must be avoided. Ignoring the magnetic field vectors shown in Figure 5-1, the RF energy propagated in a dielectric may be viewed as an electric field varying sinusoidally and diminishing in amplitude as energy is lost to the dielectric material.

Water is the most important dielectric material in the soils at Site S-1, and most of the RF energy expended in the soils served to heat and vaporize soil moisture. As mentioned earlier, the moisture is important in the decontamination process and the energy was not wasted. Most organic compounds that have only covalent bonds, such as simple alkanes, are relatively nonpolar and will not respond strongly to an electric field. Compounds with ionic bonds will respond more strongly, with the energy absorption being proportional to the dipole moment of each molecule.

The following characteristics of dielectric heating are critical in the RF soil decontamination process:

- The energy absorbed is proportional to the square of the electric field intensity.
- The energy absorbed is proportional to the frequency of the applied RF energy.
- The depth of penetration is inversely proportional to the frequency of the applied RF energy.
- The energy absorbed is proportional to the soil conductivity. Conductivity is, in turn, inversely proportional to permittivity, an important soil parameter measured by IIT. IIT's measurements of soil dielectric properties show that the variables change in a dramatic and complex manner as soil heating progresses (see Appendix A.1).

Field intensity and frequency may be varied to optimize the process, within the following limitations:

- Increasing the field intensity too rapidly or too greatly may lead to overheating in some soil volumes or electrical arcing.

- Increasing the frequency will increase the rate of heating, but reduce the depth of penetration.

The selection of startup settings and subsequent optimization of the process requires a thorough knowledge of the process, much of which must be gained by experience. Information IIT and KAI gained in prior tests at other sites was directly applicable to the operations at Site S-1. IIT recommended beginning operations at a frequency of 6.78 megahertz, then shifting to 3.4 megahertz as the soils dried out and became more transparent to RF energy. Budget considerations reduced the time available for the KAI demonstration. KAI selected on operating frequency of 27.12 mHz to take advantage of more rapid heating at higher frequencies.

The following documents provide excellent, detailed discussions of RF propagation in free space and contain important details about the Health and Safety aspects of operating RF equipment:

- Air Force Technical Order 31Z-10-4. Chapter 6 is enclosed as Appendix G.

- AFOSH Standard 161-9, Exposure to Radio Frequency Radiation. This document is enclosed as Appendix H.

5.5 BASIC COMPONENTS OF RF HEATING SYSTEMS

An RF heating system consists of the eight major components described below. The first five components would be very similar in a new design for use of either the IIT or KAI technique. The major differences in the techniques lie in the RF transmission and application components. Appendix A.1 contains a demonstration report prepared by IITRI. It includes details about their RF system and soil test data from their laboratory.

AC Power System

Existing power lines, as used at Site S-1, or portable generators are suitable power sources. Single-phase current (110 and 220 volts) is required for lights, instruments, and light power tools. Three-phase current (typically 440 or 480 volts) is required for the RF source and cooling system. Step-down transformers may be required, depending on the line voltage available at a site. Rental transformers are economical alternatives to purchasing enough transformers to suit many situations. The AC wiring to an RF system is similar to standard commercial wiring. Aerial or underground lines are suitable, and a watt-meter may be placed at a power pole or at the AC distribution panel.

A high-voltage power line lies immediately west of Site S-1. Power to the RF sources was delivered through overhead air breakers, an underground line to a rental step-down transformer, and underground lines to the trailers housing the sources. Two AC power problems developed during the tests. First, base electrical diagrams show the high-voltage line as part of a 13, 800-volt grid. Measurements indicated that the actual voltage was closer to 13, 200 volts. Second, aluminum underground power lines between the transformer and the RF source worked well during the IIT test and were installed at the beginning of the KAI demonstration. The IIT RF source, a few decades old, was designed to operate under adverse conditions and worked well on the supply line. The KAI source is a much newer, more efficient unit, and the four percent voltage drop was immediately apparent in the power output. The voltage drop resulted in an increase in current, and the aluminum-to-copper spices at each end of the underground line overheated and failed. Replacing the aluminum lines with copper ones stopped the overheating, but the KAI test continued at slightly reduced available power.

Following the KAI demonstration, HNUS personnel encountered power line problems during the installation of a groundwater treatment system at Site S-1. A large, three-phase compressor motor burned out shortly after being placed in service. The electrical subcontractor observed large fluctuations in voltage between the three phases. Kelly AFB Exterior Electric workers found a burned splice in one of the lines providing high voltage to the site, and repairing the splice returned service to normal.

KAI and HNUS had measured the voltages from ground to each of the three legs (ground to Phase 1, ground to Phase 2, and ground to Phase 3). Small, but acceptable variations appeared in those measurements. The subcontractor located the problem by measuring the voltage differences between phases (phase 1 to phase 2, phase 2 to phase 3, and phase 3 to phase 1). Kelly AFB personnel confirmed that the variations originated in the high-voltage line and worked backward along the line to locate the defective splice. The date the line was damaged is unknown, but it could explain the difficulty KAI experienced in maintaining proper line voltage.

RF Source

RF sources are like standard radio transmitters, but simpler and more rugged. The equipment must withstand travel from site to site and may be subject to a wide range of environmental conditions. Unlike radio transmitters, RF sources for soil heating require no audio frequency amplifiers or modulators. The principal components include:

- A power supply that converts AC to DC at a wide range of voltages.
- A crystal-controlled oscillator that generates an RF current at the desired radio frequency.
- Two or more stages of amplifiers that increase the strength of the RF current from the oscillator.
- A final amplifier that increases the RF current to the desired output level.
- A tuning network that matches the output of the source to the impedance of the transmission line and applicator system.

Semiconductors have replaced vacuum tubes in most active circuits in RF sources except in the final stage of amplification. Fully solid-state sources are available with outputs of 40 kW or more. Some vendors suggest that such units may be more prone to damage in harsh environments or when subjected to rapidly changing loads. Vacuum tube final amplifiers are still widely used in communications and are suitable for RF heating applications. General Electric investigators reported frequent failures with their vacuum tube source (Edelstein et al, 1994), but the IITRI and KAI sources worked well during the demonstrations at Site S-1.

The IIT RF source was a converted radio transmitter capable of providing 40 kilowatts of RF power. The physical size of the source was somewhat larger than necessary because it contained unneeded audio amplifiers, a modulator, and other equipment once used for voice transmission. Those components were turned off during the test and consumed no power.

KAI used a newer, more efficient, and more compact 25-kilowatt source.

Cooling System

All components in an RF source generate heat, especially the power supply and final amplifier. Cooling system design must be guided by both the electronic design and the anticipated operating environments. Air cooling may be adequate for sources of 20 kW or less, while substantially larger units may require refrigeration units. A system designed for year-round operation in Texas will need more cooling capacity than one dedicated for use in Oregon. In very hot climates, cooling may require ten to fifteen percent of the total AC power consumed. The IIT and KAI systems operated with no cooling malfunctions during the demonstrations.

Monitoring and Control System

Simple voltmeters and ammeters are used to monitor critical voltages and currents in the source. Other instruments display the operating frequency, the percent of RF power reflected from the applicator, operating hours, and similar basic measurements. All critical measurements should be available as digital signals recorded by computer. The computer and sensors in the source may turn off RF power if a potentially dangerous or damaging condition develops.

Much of the operation, including output tuning, should be automated. Both IIT and KAI have developed automated monitors with the capability to perform small adjustments, alert operators if other adjustments are needed, and contact operators by pager if a more serious condition develops. The systems may be interrogated by telephone modem, and data can be transmitted to remote locations. Recent developments in communications permit economical automation and reduction of labor on site.

The electric field at the site should be monitored as a safety measure, and measurements should be recorded for documentation. Routine measurements of the electric field and any radiation occurring at spurious frequencies can document that the system does not interfere with communications, television, or other RF systems.

Shelter

IIT operates their RF source from a small semi-trailer. KAI uses a custom-built trailer that can be towed behind a pickup truck with a heavy-duty rear axle. Both provide permanent housing for an RF source, an AC distribution system, a cooling system, the monitoring and control system, and a small office and storage area. Systems can be assembled in a wide variety of vehicles or in rolloff boxes that can be moved by flatbed truck, train, or airplane.

RF Transmission Line

IIT and KAI used rigid, copper coaxial transmission line which is available in lengths up to twenty feet. Universal couplings allow the coaxial line to be placed in nearly any configuration. Flexible coaxial line is available, but expensive compared to the rigid line. Either must be purged with dry nitrogen to eliminate internal moisture and prevent arcing.

The transmission line used by IIT included a matching network to compensate for the capacitance of their applicator system and RF chokes to reduce reflected radiation. The KAI transmission line contained only a switch that allowed operation of either of two applicators from a single feed line.

Applicator System

IIT and KAI used proprietary applicator systems that are described more fully below and in Appendices A.1 and B.1. Briefly, the IIT applicator system consisted of three rows of copper pipes installed in borings. The electrodes, with the soil in between as a dielectric, simulated a large capacitor. KAI used antenna-like applicators inserted into non-metallic casings. Small towers allowed KAI to move the applicators up and down in the casings as desired to heat soils at different depths.

RF Shielding

A grounded metal shield over the heated volume is required to prevent exposure of site workers to excessive RF radiation. IIT used a tunnel-like shield made of corrugated aluminum. The shield provided protection for sensors inside, and its height was sufficient to eliminate electrical arcing inside. The KAI applicator was completely below grade, so a flat grid of grounded cables and expanded aluminum sheet could be placed directly on the surface of the heated zone.

5.6 RF SOIL HEATING TECHNIQUES

The proprietary RFH techniques developed by IIT and KAI are the most prominent in current use. Both companies have performed several pilot-scale and field demonstrations. IIT is preparing a 100-

kW system, and KAI plans to build additional 25-kW units. The increases in power output will allow each to demonstrate RFH on a larger scale.

The RF sources currently used by IIT and KAI are similar in most respects. Each has a crystal-controlled oscillator that generates a low-voltage signal at the desired frequency. Two or more stages of amplifiers are typically used to amplify the signal before it reaches the final amplifier. The final amplifier provides the high power necessary for soil heating. Each system includes large power supplies, automatic monitoring and logging equipment, and cooling systems. Semiconductor devices have replaced tubes in most components of modern systems. Tubes are still used in the final amplifiers of many RF sources, including those used by IIT and KAI.

The IITRI and KAI systems reflect the nature of the parent organizations. IITRI is a not-for-profit organization, and their interests lie in the research and development of technologies. KAI, a for-profit business, has focused more closely on assembling a system that can be set up quickly and operated with a minimum of manpower. Both technologies are suitable for commercial operations. IITRI is capable of building a more fully automated system.

5.6.1 The IITRI Capacitor Technique

The IITRI technique, as demonstrated at Site S-1, uses rows of electrodes in the soil to heat a volume of rectangular cross-section. Heated volumes at Site S-1 were bounded by two rows of vertical ground electrodes, and RF energy was applied to a third electrode row midway between the ground rows. The three electrode rows acted as a large, buried, tri-plate capacitor, with soil serving as a dielectric medium between the plates. As RF energy was applied to the electrode array, soil heating began at the center, then proceeded outward and downward as designed.

The electrical impedance of the electrode array must match that of the RF source, just as the impedance of a television antenna is matched to that of the receiver. The impedance of the array changes sharply as the soils are heated to the boiling point of water, then remain relatively constant until most soil moisture is removed. The soil temperature will begin to rise again as the soils become dry, resulting in another large change in impedance. Much of the energy will be reflected back toward the RF source if the impedances are not matched. A large mismatch can result in a waste of energy and possible damage to the RF source. IIT's measurements indicated that the range of impedances that must be matched were large, requiring two matching networks to assure efficient transfer of energy to the soils.

HNUS and IITRI originally planned to incorporate the exciter electrodes into the SVE system. The objective was to remove vapors through hotter, more permeable soils. A Pyrex® tube and an additional RF choke were to be installed between the electrodes and the vacuum source to insulate the vacuum source from dangerous RF currents. However, IITRI experienced difficulty keeping the glass tube intact in a previous test at Rocky Mountain Arsenal, and the idea was not tried at Site S-1. The concept has merit and could be tested if suitable materials can be found.

IITRI has demonstrated the ability to heat a well-defined volume uniformly. Drawbacks include the need for a large number of electrode and sensor borings and the potential difficulty of matching a wide range of impedances. However, the IITRI matching equipment tracked impedance changes well during the demonstration and relatively few manual adjustments were necessary.

HNUS and IITRI elected to observe the effects of continued heating after much of the soil volume had reached the target temperature. Portions of the heated volume were heated to nearly 1000 °C and the system was turned off when power fluctuations indicated that electrical arcing might be occurring below grade. Post-test drilling revealed molten pieces of electrodes and thermocouples.

5.6.2 The KAI Antenna Technique

KAI Technologies, Incorporated, uses an antenna-like applicator inserted in a single boring to heat a cylindrical soil volume. The antenna is an end-feed dipole that can be tuned by adjusting its length, inserting or removing ceramics blocks inside the antenna, or both. The technique is less sensitive to changes in soil dielectric properties. Energy from multiple applicators can be electrically phased to heat larger volumes of soil. An antenna can be moved along a horizontal borehole to treat soils beneath structures, roads, or runways. In vertical applications, the antenna may be positioned to preferentially heat a layer or layers of contaminated or relatively impermeable soils. Drawbacks include the need to treat overlapping cylindrical volumes and the possible need to construct site-specific antenna applicators.

The system deployed at Site S-1 included two antennas suspended from aluminum towers. KAI planned to switch RF power from one antenna to another and move the antennas up and down periodically to heat a soil volume similar to that enclosed by IITRI's electrodes. However, full-power operation began later than planned because of a delay in receiving permission to operate and the need to replace the main power line to the system. Most of the demonstration was conducted using a single antenna at a single depth because of time and budget constraints.

System setup proceeded very quickly. All mechanical work and most electrical work was completed in three days. Full-power testing could have begun in less than a week if permission had been granted.

The delays mentioned above left little time for full-power operation or testing different configurations of the RF equipment. With the exception of some minor problems, the equipment performed well with little operator attention. Exceptions include:

- A coaxial line developed a nitrogen leak immediately before a holiday weekend, when deliveries were unavailable. The nitrogen loss eventually led to internal arcing that damaged the antenna's central conductor.
- KAI found that the spare central conductor had broken in shipment to the site. The stress fracture indicated the need for improved packing.
- The reduced line voltage described above revealed that some subsystems in the KAI RF source were sensitive to low voltage. KAI has installed an uninterruptable power supply to maintain proper operation when the final amplifier is switched on.

The KAI system includes extensive monitoring devices and a central control computer. When off site, operators can communicate with the system by telephone or radio. For example, Mr. Faust used a variety of communications equipment including two-way radios, pagers, cellular and land-line telephones, and a notebook computer. He could interrogate the RF system from his truck or motel room, and the system alerted him by pager if a monitored parameter exceed pre-set limits.

5.7 DESIGN CONSIDERATIONS

This section presents elements that must be considered in designing a system. Most components are readily available or relatively simple to build, but the design still requires the expertise of engineers with broad training and experience. An Air Force or HNUS team, for example, could prepare an excellent design, but the process could be greatly expedited by incorporating the experience of workers who have thoroughly investigated the mechanisms of soil heating.

5.7.1 Time and Energy Requirements

The following relationships are useful in estimating electrical heating costs:

1 kilowatt ≈ 56.9 Btu per minute

1 kilowatt-hour ≈ 3,413 Btu

Knowing the unit cost per kilowatt-hour, one could calculate the energy cost and heat output for a simple resistive heater with reasonable accuracy. Calculating more realistic time and energy requirements for RF soil heating requires additional knowledge of electrical conversion efficiencies and soil characteristics.

Two examples below illustrate useful procedures for estimating time and energy requirements for RF soil heating. Each may also be used to determine the RF power required to complete a heating task within a predetermined schedule. The first example is appropriate for use early in a project to provide initial estimates of RF power and manpower needs. The second example provides more realistic estimates, but requires more specific knowledge about the electrical properties of the soil. In situ measurements could be made during an SVE pilot test to minimize time and labor.

1) Kasevich et al presented the following simple example in seminars sponsored by the University of Wisconsin (Kasevich et al, 1991):

   Assume that the objective is to remove 1,2 dichloroethene (DCE) from 400 cubic yards (10,800 ft^3) of soil. Assume an efficiency of 95% for the applicator (KAI), a 70 % thermal efficiency for the soil heating, and energy costs of \$0.06/kW-hour The boiling point of 1,2 DCE is 60° C, and investigators plan to heat the soil to 70° C. The thermal energy required to heat one cubic foot of soil to 70° C is 0.934 kW-hour/$foot^3$ (from literature search). Small heat losses at the surface and variations in contaminant and soil moisture distribution are ignored.

   $$\text{Thermal energy required} = 0.934 \text{ kW-hr/ft}^3 \times 10{,}800 \text{ ft}^3 = 10{,}087 \text{ kW-hr}$$

   Allowing for application efficiencies:

   $$\text{Thermal energy required} = \frac{10{,}087 \text{ kW-hr}}{(0.95)(0.7)} = 15{,}168 \text{ kW-hr}$$

The time required to heat with a 20-kW RF source is:

$$15{,}168 \text{ kW-hr} \div 20 \text{ kW} = 758 \text{ hours} = 31.6 \text{ days}$$

Assuming an RF source efficiency of 50% (including cooling and other ancillary systems):

$$\text{Energy costs} = \frac{(15{,}168 \text{ kW-hr})(\$0.06 / \text{kW-hr})}{0.5} = \$1{,}820 = \$4.55 / \text{yd}^3$$

The actual time may vary, and supplying the energy in pulses may be more efficient than continuous heating. The example still illustrates two points. First, 1,2 DCE will be quickly desorbed. Second, the electrical energy costs are low.

Additional time and energy will be required if the target temperature is at or above the boiling point of water (soil moisture). Cost estimates must include the time and energy required to raise the water temperature to 100° C, then supply additional energy to boil the water to evaporation. However, water removal often expedites contaminant removal, as discussed in other sections.

2) A more site-specific approach includes determining the dielectric properties of the soil and, concurrently, monitoring the energy required to heat a discrete soil volume. This approach is particularly valuable in optimizing an electrode design for application of the IITRI technique. The measurements may be performed in situ or in a laboratory. In situ measurements are more reliable because the soil is relatively undisturbed and moisture and contaminants are not lost in handling. In either case, a small soil volume is monitored during exposure to an electric field to determine its conductivity, resistivity, and specific heat.

The following equation indicates the power (P), in watts, absorbed per cubic meter (W/m^3) of the soil matrix:

$$P = \sigma[E_{rms}]^2 = [E_{rms}]^2 / \rho$$

where:

E_{rms} = the root mean square of the applied voltage (volts)

σ = the apparent conductivity of the material at a given frequency (mho/meter)

ρ = the apparent resistivity of the material at a given frequency, moisture content, and temperature (ohm-meter).

The specific heat (measured) and the power absorption (calculated above) permits calculation of the required RF energy (W_R) as in the example above. The system-specific efficiency, E, is determined from data gathered during the pilot studies. The time (t) required for heating is then calculated as follows:

$$t = (W_R/P_A)\ E_f$$

where:

- t = time required for heating (hours)
- W_R = energy required (kW-hr)
- P_A = power available (kW)
- E = efficiency (%)

Early plans for the demonstration phase of this project included purchase of a 120-kW RF source. One 120-kW RF source would require approximately 1100 hours (48 days) of uninterrupted heating to heat 500 cubic yards of soil (similar to the soils at Site S-1) to 150° C (IITRI, July 1992). In the example below, the time and energy costs for heating the demonstration volume are computed assuming that use of a 240-kW RF source will reduce the heating time by half (i.e., Scale-up to larger volumes results in directly proportional heating times). IITRI also suggested that the transmission and RF conversion efficiencies should be 65% and 80 %. Energy costs for continuous heating of the entire site, about 6230 yd^3 or 10,000 tons, are as follows (using two sources):

Time to heat = (6230 yd^3 / 500 yd^3) x 1100 hr / 2 = 6853 hours (285 days)
Energy required = 240 kW / (0.65 x 0.8) x 6853 hours = 3,162,923 kW-hr
Energy cost (assuming $0.06 / kW-hr) = $189,775
Unit cost for AC energy = $189,775 / 6230 yd^3 = $30.46 /$yd^3$ or $18.98/ton

The vapor extraction and treatment system, plus lighting and office power, add relatively small costs.

The second cost estimate is noticeably higher (by a factor of 6 or 7) than the first, although Kasevich assumed a more conservative overall heating efficiency. A major reason for the disparity is that literature values of specific heat (as used in the first example) are usually for dry soil, whereas the measured values used in the second include soil moisture. Also, the second example includes dielectric losses not included in the first.

The treatment cost per ton must be evaluated in terms of specific project objectives, including the significance of in situ treatment. Like most remedial technologies, RFH has certain fixed costs, including equipment amortization and mobilization/demobilization costs. These costs are more significant in very small projects than in very large ones. However, RFH might be very economical for small projects if the contaminated soil lies in a critical location. A technique with a relatively high treatment cost per ton might be a very economical solution if the tons to be treated lay beneath a building or a busy runway.

5.7.2 The RF Source

As mentioned earlier, tube-type sources have functioned well for IITRI and KAI. Many vendors offer a wide variety of units rated up to 200 kW or more. All-semiconductor sources are available in smaller sizes, and larger units will be available in a few years. Selection is complicated by factors other than total power output:

- Two hundred kilowatts can be delivered by a single large sources, eight 25-kW units, or other combinations of sources. Systems maybe connected by fiber optic lines and controlled from a central computer/logger. A 200-kW source can be used to deliver 10 or 20 kW for small applications, but hardware and amortization costs might be prohibitive. Relative costs are explored further in Section 8.
- Semiconductor sources are much more efficient, but vacuum tube amplifiers are more tolerant of voltage and current excursions. The greatest AC to RF conversion efficiency is available in state-of-the-art sources with semiconductor amplifiers operating a temperatures near room temperature. Cooling requirements are stringent, however, and cooling costs and higher purchase price may offset the savings of RF conversion efficiency. As noted in Section 5.7.1 and Section 8, energy costs for RFH are low compared to labor and equipment costs.
- The type of service anticipated could influence source selection, and housing equipment destined for extremes of climate or vibration could add substantially to hardware costs.

5.7.3 Applicator Selection

The IITRI and KAI systems differ most below grade, at the applicator system. With appropriate licenses, an RF system could be built to use either the IITRI capacitor and the KAI antenna applicators. The IITRI systems heats fairly regular blocks of soil. The shape of the KAI treatment zone is less regular, but fewer borings are required. Additionally, the KAI antenna may be moved to assure full vertical coverage or additional heating of clay lenses. A horizontal application would require the use of an antenna.

5.7.4 Ancillary Equipment

Labor has been the major cost in the development of RFH. Monitoring, logging, and communications equipment costs little compared to maintaining a large, skilled crew on site. Equipment should be selected to perform the following functions:

- A central system must collect and record data. This data should include operational data (temperatures, power usage, etc.) and the data need to document safe operations, such as periodic, aboveground electric field measurements.
- The data collection and logging functions must include controls to turn off the RF source if operating parameters exceed preset limits.
- The computer must also be able to alert off-site personnel of alarm conditions and report operational measurements. Recent advances have reduced the cost of most of the communications equipment.

Additional equipment is required for routine monitoring of voltages, currents, voltage standing wave ratio, and frequency. Some items are costly, but have long useful lives. When amortized, they do not add greatly to a system's costs.

5.8 LESSONS LEARNED AT SITE S-1

IITRI and KAI demonstrated the ability to effectively heat soils containing dense clays. Neither demonstration produced optimal heating due to minor correctable problems Other lessons are discussed below

5.8.1 Preplanning Phase

- HNUS asked for bids for a 120-kW RF source for use in Phase 2 of the project. The range of costs received was so large as to be meaningless. The large range resulted from vendor's misunderstanding of requirements and indicated that the specifications were too broad. Prior to formally requesting bids, a potential user should discuss his needs at length, perhaps by teleconference, with all potential bidders. Requests for bids must be sufficiently specific to ensure a fair comparison.

- All parties underestimated the effort required to obtain permission to operate an RF source at a military facility. The concerns of the base communications personnel were understandable; their mission is to maintain secure communications and flight operations. Two factors complicated the application process. First, a typographical error indicated a requested frequency in kilocycles instead of megacycles, leading in turn to an inquiry to the FCC. The error was corrected promptly, but the resulting confusion caused a few day's delay. Second, some personnel were somewhat confused about an antenna that appeared to be upside-down (underground). Problems like these will stop when the technology becomes more well-known. Even on military reservations, clearance should consist of documenting ISM frequency use and assuring that proper aboveground monitoring will be conducted.

5.8.2 The IITRI Demonstration

- One of the project goals was to extend the heating as deep as possible into a clayey soil. HNUS installed four dewatering wells and pumps to depress the water table during the demonstration. Dewatering was generally successful, but shorting at the bottoms of the electrodes may have occurred late in the IITRI demonstration. Dewatering may be useful to prevent shorting at sites where groundwater levels vary widely, but the pumping is probably not a useful way to extend the depth of heating.

- Recent developments in soil and groundwater sampling include tubes that can be pushed into the ground without drilling. Some require a drill rig to advance the tubes, while others may be pushed with a backhoe. By potentially eliminating the need for drilling, they offer substantial cost savings for electrode installation. These devices are unlikely to work well at Site S-1, but could substantially reduce installation costs in sandy or loamy soils.

- The IITRI demonstration showed that an old source in a semi-trailer shelter can provide very useful soil heating. Such units are inexpensive, rugged, and able to withstand large voltage and impedance changes. Users who anticipate purchasing several sources should buy new, interchangeable components, but others might be wise to investigate surplus sales for obsolete commercial or military gear.

- The corrugated shield over the heated soil served two purposes, preventing stray RF emissions and capturing vapors that might escape to the surface. Vapor monitoring showed that the SVE system captured soil vapors effectively, so the additional capture volume was unnecessary. However, the corrugated metal provided an effective and reusable RF shield.
- Extracting vapors through the exciter electrodes is desirable because vapors are unlikely to condense in the hot soil near the center of the array. Further materials research may lead to an electrically insulating material suitable for use with hot vapors.

5.8.3 The KAI Demonstration

- KAI elected to use small aluminum towers to support their antennas and move them vertically. If rigid coaxial line is used, the height of these towers must be approximately the same as the depth of the antenna wells. The towers can present a hazard in high winds, and operations might be curtailed in stormy weather. The antenna depth can be adjusted by adding or removing sections of coaxial line. However, changing rigid sections requires reestablishing the nitrogen purge and retuning the RF source. Flexible coaxial line is more expensive, but would allow the antenna to be supported by a shorter, simpler structure while maintaining a constant feed line length.
- KAI showed that off-site monitoring of a relatively complex operation is both feasible and practical. KAI had no difficulty maintaining telephone communication with the system from a motel room, about five miles from the site. A pager received alarm messages and routine status reports. In commercial use, a remote operator could interrogate systems at several sites daily, perform any required data reduction, and prepare a status report for each.
- The two composite casings that housed the KAI antennas were costly. Less expensive materials that tolerate higher temperatures were available by special order, but the lead time between placing an order and delivery to the site was unacceptable for the project. Preparations for a large project should include a reevaluation of available products and allowance in the schedule for any extended deliveries.

5.8.4 Both Demonstrations

- IITRI and KAI demonstrated RFH while meeting health, safety, and communications requirements for surface RF emissions. On-site radios, cellular telephones, and television sets operated without interference, and no stray emissions were detected on incoming power lines.

- IITRI and KAI attempted to monitor subsurface temperatures with fiber optics probes. The probes could be especially useful to monitor temperatures near the KAI antenna casings or other objects subject to very localized and potentially damaging high temperatures. These devices have provided excellent results in many applications, including medical and nuclear laboratories, but the results at Site S-1 were disappointing. Both vendors reported only limited success with the probes. The devices offer so much utility that improvements will probably follow quickly.

- Both vendors used strings of thermocouples successfully. The devices are inexpensive and easy to use, but not very accurate near ambient temperatures. The accuracy is probably no better than ± 10%, but that range should be adequate for most measurements during RFH.

- IITRI and KAI turned their RF sources off periodically for measurements or repairs, and both vendors experienced shutdowns due to measured parameters that activated alarms. Power failures during storms occasionally shut down all site operations except the SVE system. These outages, which rarely lasted longer than a few hours, had little negative impact on soil temperature patterns (see Appendices A and B). On the contrary, shutdowns may tend to smooth out temperature variations caused by local "hot spots". If so, periodic maintenance operations could be scheduled to improve the uniformity of heat patterns.

- Many functions in an RF soil heating project, including plan development, site preparation, sampling, air monitoring, and reporting, are very similar to those required for other remedial technologies involving equipment of similar size. The RF source operators need special skills and experience, but other site workers need only routine hazardous waste site training.

6.0 SOIL VAPOR EXTRACTION

This section includes background information on SVE systems, a brief description of the systems used during previous RFH tests, and detailed descriptions and evaluations of the systems used during the demonstrations at Site S-1, Kelly AFB. The background sections provide basic information necessary for a general understanding of the processes that occurred during the demonstrations. The design and operation of the systems used at Site S-1 by IITRI and KAI are discussed in subsections for each heating method. The lessons learned from the evaluation of data and field experience conclude this section.

Although often SVE has become widely accepted for the removal of VOCs from high permeability soils, SVE is not an efficient process for remediating lower permeability soils or less volatile compounds. Using RFH to enhance SVE should increase the vapor pressures of the contaminants and improve the soil permeability, making SVE a more attractive treatment option. Section 6.1 includes a discussion of the theories behind SVE with an emphasis on how RFH affects the design and operation of an SVE system. The lessons learned by operating the systems described in Section 6.4.

6.1 BACKGROUND

The following subsections discuss the basic concepts of SVE and the design and operation of an SVE system. The subsection on the basic concepts includes a description of contaminant phases and transport. Although these concepts may sound complex, SVE is a rather simple solution for in situ soil remediation.

6.1.1 <u>Basic Concepts</u>

SVE removes contaminants in the vapor phase from the vadose zone by inducing a vacuum at an extraction well and pulling air through the contaminated zone to the extraction well. However, contaminants exist not only as a mixture of vapors in the vadose zone but also as thin films or globules of solution (aqueous or organic) and nonaqueous phase liquids (NAPLs), as solids, and sorbed to the soil particles. Under static conditions contaminant concentrations in each phase are at equilibrium. The equilibrium concentrations are determined by the chemical and physical properties of the contaminant.

The vaporization of NAPLs, free-phase or in solution, is governed by Raoult's law and Henry's law respectively. Raoult's and Henry's laws describe the relationship between the partial pressure of a contaminant and the mole fraction of the contaminant as shown in equations (6-1) and (6-2) respectively (Felder and Rousseau, 1986).

Raoult's Law: $$p_A = y_A P = x_A p^*_A(T) \quad (6\text{-}1)$$

Henry's Law: $$p_A = y_A P = x_A H_A(T) \quad (6\text{-}2)$$

where:

p^*_A	=	partial pressure of compound A in the gas phase
y_A	=	mole fraction of A in the gas phase
P	=	total pressure exerted on the liquid
x_A	=	mole fraction of A in the liquid phase
$p^*_A(T)$	=	vapor pressure of the pure liquid at temperature T
$H_A(T)$	=	Henry's law constant for A in a specific solvent at temperature T

Since Raoult's law is only applicable for almost pure substances, it can be used to describe the relationship between the contaminant in the gas phase and the NAPL phase. Henry's law is applicable for substances in solution such as a contaminant dissolved in the moisture in the soil. These laws state that the partial pressure of a substance is directly proportional to the concentration of the substance in the vapor phase. However, in cases where more than one substance is present the partial pressure of the mixture equals the sum of the partial pressure for each substance. Since the vapor pressure of a pure substance and the Henry's law constant for contaminants in solution increase with temperature, more of the contaminant will be in the vapor phase as the temperature increases. Heating the contaminated volume increases the rate at which the contaminant volatilizes into a mixture of vapors from the liquid phase.

If the contaminant is in the solid phase, vapor pressure will control the amount that will vaporize, or sublime. Therefore, an equation similar to Raoult's Law would describe the sublimation. Again, a temperature increase causes the vapor pressure to increase and more of the contaminant to vaporize into the gas phase.

The rate at which a contaminant adsorbs to a soil particle is released is described by a desorption isotherm. A desorption isotherm is a graphical description based on column tests in a laboratory. Since these column tests are performed under controlled conditions, the results may differ from the reactions that take place in the field.

Once the contaminant is in the vapor phase, induced air flow moves the contaminated vapors to an extraction well. A blower or ejector system induces a vacuum at the extraction well(s). The pressure gradient in the soil leads to a flow of air from the surrounding soils to the extraction well(s). The flow rate through the soil to the extraction well(s) can be estimated, assuming the equations for steady-state, compressible, radial flow are applicable, and using the following equation (Johnson et al, 1990):

$$Q = H\pi \left(\frac{k}{m}\right) P_w \frac{[1-(P_{atm}/P_w)^2]}{\ln(R_w/R_I)} \qquad (6\text{-}3)$$

where:

Q	=	vapor flow rate [SCFM]
H	=	well screen length [centimeter]
k	=	permeability to air flow [centimeter^2] or [darcy]
μ	=	viscosity of air = 1.8×10^{-4} g/centimeter·s or 0.018 cp
P_w	=	absolute pressure at the extraction well [g/centimeter·s^2] or [atm]
P_{atm}	=	absolute ambient pressure ≈ 1.01×10^6 g/centimeter·s^2 or 1 atm
R_w	=	radius of the vapor extraction well [centimeter]
R_I	=	radius of influence [centimeter]

According to this equation, changes in the screen length, the permeability, and the vacuum induced at the well will result in potentially significant changes in the flow rate through the soil. After the SVE and treatment systems are operating, the soil permeability will increase due to the evaporation of the soil moisture and the removal of condensed contaminants. The permeability changes gradually during the operation of typical SVE systems. However, the increased permeability should occur more rapidly with RFH/SVE.

Unlike the screen length, permeability, and induced vacuum, the radius of influence has little significance in this equation. The radius of influence can vary several orders of magnitude and not change the flow rate significantly. Therefore, it is important to remember that this equation only provides an estimate of the flow rate through the soil. This is particularly true when the soil is as heterogeneous as the soils at Site S-1.

Since the air will flow through the paths of least resistance to the extraction wells, heterogeneities in the soil lead to preferred pathways. Some areas will be remediated by advective transport of the contaminants. Diffusion transports contaminants from areas of lower flow to areas with higher flow rates. Since transport via diffusion is much slower than advective transport, preferred pathways should be avoided by installing wells in lower permeability soils, utilizing vapor barriers, and varying the extraction pattern during operations. Screening some of the wells over the bottom half of the volume and others over the top half of the volume may help minimize the development preferential pathways. When using RFH, preferential pathways are expected to develop in the heated area.

The transfer of contaminants from soil pores to the vapor stream may be limited by phenomena other than diffusion (Reinhart et al, 1994). The rate at which contaminants trapped in soil pores diffuses into the vapor stream limits the concentration of the contaminant in the vapor stream. If the flow rate is too high, the contaminant may not be detected in the vapor stream even though the concentration in the soil may be above the treatment goals. This phenomenon has occurred numerous times at sites using typical SVE systems. The contaminant concentration in the vapor stream indicates that the soil is clean, but soil sampling reveals that the soil concentrations are still above action limits. The flow rate should be decreased when vapor stream concentrations have decreased. The diffusion rate will be higher at higher soil temperatures than at ambient temperatures.

6.1.2 Design and Operation

Extraction, Monitoring, Passive, and Injection Wells

The most basic SVE systems utilize extraction wells to remove the contaminants and monitoring wells to observe the subsurface pressures. Some systems utilize passive or injection wells to increase the flow of clean air through the soil or to create a barrier to flow entering the treatment zone. The difference between passive and injection wells is that passive wells are open to the atmosphere and clean air is injected through the injection wells into the treatment zone. The path of least resistance to air flow from the surface would be the passive or injection well. Thus the passive and injection wells form the edge of the treatment zone. The change in the pressure gradient creates a barrier to the flow of air through the soil, across the line of passive or injection wells.

The SVE system can be designed so that any well can serve as extraction, passive, or injection wells. This allows the system to be operated at a variety of configurations but requires that the wells be of the same construction and properly manifolded. A flexible SVE system allows the extraction configurations to be altered to prevent preferential pathways and adjusted to current site conditions. However, the wells must be constructed of the same size and type of casings. The casing material must be compatible with the contaminants and the soil. When using RFH/SVE the casing materials must also withstand the design temperatures.

Since the induced vacuum will locally raise the water table, the bottom of the screens must be above the water table. In order to prevent pulling groundwater through the extraction wells, they should be installed such that the maximum vacuum at the well (in inches of water) is the minimum distance between the bottom of the screen and the water table.

Although most SVE systems use vertical wells, horizontal wells and trenches are also used. Horizontal wells allow extraction systems to be installed in locations where objects such as buildings prevent installation of vertical wells. When using a RFH/SVE system, horizontal wells at the surface provide a way to quickly extract vapors that rise to the surface and collect under the vapor barrier. The pressure at these wells should be monitored. As long as the horizontal wells are under the influence of the vertical extraction wells, the vapors should not be collecting at the surface.

Number and Location of Extraction Wells

Although the radius of influence has little impact on the flow rate, the radius of influence and the geometry of the contaminated zone typically determine the number and location of the extraction wells. The minimum number of wells required equals the minimum number of circles with radii equal to the radius of influence of the extraction well that will cover the contaminated volume. The extraction wells would be located at the centers of the circles. Although a rule-of-thumb radius of influence [30 to 100 feet (Johnson and Ettinger, 1994)] will provide a rough estimate of the number of wells required, a pilot scale field test provides a more accurate estimate of the radius of influence and a better estimate of the number of wells required to remediate the site.

The site-specific radius of influence is determined by performing a field test in which the vacuum induced at a single extraction well and the subsurface pressure responses at monitoring wells are recorded. Existing monitoring wells can be used for this test if they are screened above the water table and are not located too far apart. Usually the test is performed over an expected range of operating vacuums. During the test the following data is collected:

- flow rate from the extraction well,
- vacuum at the extraction well,

- subsurface pressures (vacuums),
- atmospheric pressure, and
- vapor stream temperature.

The screened length of the extraction well and the distances from the extraction well to the pressure monitoring wells are known. The subsurface pressures are plotted versus the distance from the monitoring well to the extraction well. The point where a line fit to these points intersects the axis representing the distance from the extraction well indicates the radius of influence. For practical purposes the radius of influence is assumed to be between 0.1 and 1 inch of water or 1 percent of the induced vacuum.

Current efforts attempt to base the number of wells on the contaminant concentration and desired remediation time (Johnson and Ettinger, 1994). Johnson and Ettinger use the following equation to determine the number of wells:

$$N_{wells} = \frac{\alpha M_{cont}}{Q_{well} T_R} \qquad (6\text{-}4)$$

where:

N_{wells} = minimum number of wells required to remediate the site

α = min. volume of air per unit mass of contaminant required for remediation (m^3/kg)

M_{cont} = mass of contaminant present (kg)

Q_{well} = estimated flow rate to a single well (m^3/s)

TR = desired time for remediation (s)

However, if Reinhart's theory that diffusion controls the desorption rate is correct, estimating the number of wells required to remediate a site is very difficult because the time of remediation is controlled by the diffusion rate. The result of equation (6-4) should be compared to the number of wells determined using the geometry-based method. The method that results in the greater number of wells should be used.

When integrating an RFH and SVE system, the location and number of wells may be based on the requirements of the RFH technology. IITRI's system limits the extraction wells to the ground electrode rows that bound the heated area. Thus with IITRI's system the contaminants must be pulled from the middle of the heated zone to the ground electrodes. Another option with KAI's system is to install the extraction wells near the antenna well and pull the contaminants to the middle of the heated zone. In both cases the geometry of the heating system or the heated zone influence the location of the extraction wells.

Extraction Force

Typically some type of blower will be used to induce the vacuum at the extraction wells. The blower must be sized to provide the desired vacuum and flow rate at that vacuum. In order to meet health and safety standards, the blower must be explosion proof if there is any risk of an explosive mixture. The blower materials must also be compatible with the vapor stream, which may be corrosive. If the vapors condense into droplets, the droplets can cause excessive blower wear.

Although most designers use blowers to induce the vacuum for a SVE system, other options are available. An ejector assembly was used to induce a vacuum at Site S-1. An ejector is a specially designed venturi with a tee in the narrow section. Forcing air through the narrow section of a venturi induces a negative pressure at one end of the venturi. The Site S-1 system is discussed in Section 6.1.3 and Appendix D.

Manifold System

The headers from the extraction wells should be manifolded in such a way that each well can be controlled individually. This does not mean that the vacuum at each well must be controlled separately but that any well can be used as an extraction, passive, or injection well at any time. The use of flexible hose to connect the header manifolds to the extraction force increases the flexibility of the system. However, the materials used in the piping system must be compatible with the contaminants in the vapor stream. Materials used for any heat enhanced SVE system must be able to withstand the maximum anticipated vapor temperatures. When using RFH the pipes from the wells to the manifold must also be nonconductive.

Instrumentation and Monitoring

The following parameters should be monitored with any SVE system:

- vapor stream flow rate from the wells
- vapor stream flow rate to the treatment system
- pressure (vacuum) at each extraction well

- pressure (vacuum) at each monitoring (passive) well
- pressure at each injection well
- inlet and outlet pressure at blower or ejector

The flow meters and pressure gauges must be compatible with the vapor stream and the expected conditions. The expected flow rates and pressures should be in the middle of the range of the meter or gauge.

When using RFH to enhance vapor extraction, temperature gauges should be used to monitor the vapor stream temperature from each extraction well, the inlet to the blower, and the outlet from the blower. The moisture content and temperature of the vapor stream will change as the soil temperature increases. Since most flow meters are designed to be accurate over a narrow range of temperature, the change in temperature makes it difficult to find a flow meter for this application. The density of the vapor stream changes in moisture content and temperature change. Thus flow meters that operate based on the mass flow of air will not be accurate over the full range of temperatures and moisture contents expected during operation of RFH/SVE.

Vapor Barrier

Depending on the site conditions, the SVE design may include a vapor barrier. The vapor barrier is a flexible, impermeable barrier that serves the following functions:

- prevents fugitive emissions from the contaminated zone,
- prevents air from short circuiting from the surface to the wells,
- prevents water from infiltrating from the surface through the contaminated zone, and
- assists in maintaining the vacuum within the contaminated zone.

By reducing the vertical flow of air through the contaminated volume, air will be forced to flow horizontally through the through the contaminated volume.

The impermeable material may be a paved surface or any plastic with appropriate properties. Plastic vapor barriers should be designed to be compatible with the surface contaminants and to be reused. The plastic must be stabilized so that ultraviolet light will not degrade the material. If the ground surface is rough, a layer of topsoil placed on the ground surface beneath the vapor barrier will prevent tears in the plastic. In some cases the soil cuttings generated on site may be used instead of buying topsoil. Any vapor barrier should have as few seams as possible.

In the case of RFH/SVE the vapor barrier also prevents fugitive emissions from the surface of the heated zone. The vapor barrier material must be capable of resisting maximum expected surface temperatures. A layer of insulation by be placed between two pieces of plastic to reduce heat loss at the surface.

6.2 HISTORY WITH RF HEATING

IITRI and KAI had performed earlier tests which utilized different approaches to SVE. The results of these earlier tests were considered when designing the SVE systems for the demonstrations at Site S-1.

6.2.1 IITRI

The treatment zone for the IITRI test performed at Volk Field Air National Guard Base (Dev et al, February, 1989) was in shallow, sandy soils. IITRI collected vapors rising to the surface. This approach was not applicable for removing contaminants from the depths of the treatment zone at Site S-1. Therefore, an active vapor extraction system with extraction wells screen as deep as 24 feet below the surface was utilized at Site S-1.

During the IITRI test performed at Rocky Mountain Arsenal, IITRI measured subsurface pressures and attempted to incorporate the exciter electrodes into the vapor extraction system (Roy F. Weston, 1992). IITRI included a section of glass pipe in the line to the treatment system and attempted to prevent condensation in the pipe by circulating warm air around the glass pipe. Condensate formed and the glass tubes broke (Roy F. Weston, 1992). Therefore, extracting from the exciter electrodes was not attempted the Site S-1 test.

6.2.2 KAI

During a test at DOE's Savannah River Site, KAI used a single horizontal well to house the antenna and serve as an extraction well (Jarosch et al, 1994). The final report recommended using separate antenna and extraction wells. The design for Site S-1 utilized separate antenna and extraction wells in a vertical well system.

6.3 SVE SYSTEMS USED AT SITE S-1

The SVE systems installed for the IITRI and KAI demonstrations utilized the same ejectors to provide the extraction force. However the well systems were installed in different patterns and operated differently for the IITRI and KAI demonstrations. IITRI designed the "effluent containment and collection" system for the IITRI demonstration. HNUS designed the SVE system for the KAI test to create a treatment zone similar to IITRI's, but incorporated the lessons learned during the IITRI demonstration design and operation to isolate the treatment volume. HNUS tried several extraction patterns and monitored subsurface pressures during the KAI demonstration to evaluate the SVE system.

The ejector system was designed by Brown and Root Braun and is discussed in Appendix D. Two ejectors were plumbed in parallel so one could be in service and the other was cleaned or served as a spare. Strainers were installed upstream of the ejectors to prevent clogging of the ejectors. A diesel compressor supplied the compressed air for the system. Each ejector could provide a 30 inches H_2O vacuum at 60 SCFM. Although Brown and Root Braun selected the ejectors based on IITRI's request for 10 inches H_2O, the two ejectors were capable of pulling vacuums up to 40 inches H_2O during the early phases of the KAI demonstration. The combined flow from the treatment zone and the air compressor was mixed with propane and burned in a flare.

HNUS monitored the temperature and pressure gauges and flow meters listed in Table 6-1 during the IITRI and KAI demonstrations.

TABLE 6-1

INSTRUMENTATION AND MONITORING DEVICES

Parameter to be Measured	Device	Range
Pressure on inlet line to ejectors (from the air compressor)	McDaniels Control - Tube and Socket Pressure Gauge	0-200 psi
Flow Rate through the ejector inlet line (from the air compressor)	ERDCO (Model 3211-06 TI) Flow Meter	0-200 SCFM
Vacuum in the suction line to the ejectors	Dwyer Magnehelic® Pressure Gauge (Model 2050C)	0-50 in. H2O
Pressure in the discharge line from the ejectors	Dwyer Magnehelic® Pressure Gauge (Model 2050C)	0-50 in. H2O
Temperature of vapor in suction line	Reotemp Temperature Probe	50-400 °F
Pressure in mixed vapor line (at the flare)	Dwyer Magnehelic® Pressure Gauge (Model 2205C)	0-5 psi
Flow Rate of mixed vapor to the flare	ERDCO (Model 3211-06 TI) Flow Meter	0-400 SCFM
Temperature of mixed vapor at the flare	Reotemp Temperature Probe	50-400 °F

The flow meters were selected as a cost effective way to provide relative flow rates. An extensive search by Brown and Root Braun did not find flow meters that would provide consistently accurate data for the wide range of conditions at Site S-1. Most flow meters are based on the mass flow of the vapor stream. Since the mass flow is based on the density of the vapor stream, which is a function of temperature and moisture content, measuring the flow rate is difficult with flow meters. Humidity sensors for the wide range of expected conditions at Site S-1 were not available. The flow rate could be calculated based on the pressure difference across an orifice plate. However, this calculation also requires a vapor stream density measurement.

In addition to the flow meters not reading accurately, the flow rates below 40 SCFM were not easy to read because the flow meters had logarithmic scales. The flow meters require periodic cleaning to remove corroded material from the needle mechanism.

6.3.1 The IITRI Demonstration

Design

IITRI designed their SVE system, which they called an "effluent containment and collection system". Their system was designed based on the assumption that the vapor will rise to the surface or be pushed out of the treatment volume. They also incorporated the ground electrode array into the design. IITRI's SVE system included two horizontal extraction wells (one pipe on each side of the treatment volume embedded in pea gravel at the surface) and 12 screened ground electrodes (all the ground electrodes except the four end ground electrodes). IITRI's SVE system layout is shown in Figures 8, 9, 10, 11, 12, and 13 of IITRI's Draft Final Report included as Appendix A.1 of this report.

Installation

The ground electrodes were installed as described in Appendix C. Each electrode was screened by drilling holes in the 2-inch diameter aluminum pipe. Holes were drilled the full 29-foot length of the ground electrodes. IITRI required that the ground electrode boreholes be backfilled with a mixture of sand and clay. Some of the soil cuttings from pretest sampling and electrode installation were spread over the treatment site to be treated. These cuttings formed a slight crown on the site so water would run off. The horizontal wells were placed on the ground surface and covered with pea gravel.

IITRI installed a three-layer vapor barrier over the treatment zone. The bottom layer was fiberglass-reinforced silicon rubber. A middle layer of insulation reduced the heat lost to the atmosphere. The final layer was a nylon-reinforced plastic. This barrier extended 10 feet beyond the treatment zone. The edges of the barrier were buried in a shallow trench that was backfilled with bentonite.

Operation

The dewatering system described in Appendix A.8 was operated prior to and during the operation of the RFH and SVE systems. Since the bottom of the ground electrodes was below the water table, ground water would have been removed if the SVE system had been started prior to dewatering.

HNUS tested the ejectors and extraction system and collected vapor stream samples on 24 March 1993. Site personnel experimented with the ejectors to observe the vacuums could be achieved during final RFH system checks. When IITRI started heating on 3 April 1993, the vacuum at the ejectors was set at approximately 12 inches H_2O. The average vacuum at the ejectors during the test was approximately 8 inches H_2O. The vapor extraction system was off for 4 days during cool-down. The system was restarted at a vacuum of 4 inches H_2O. Both the horizontal extraction wells and the ground electrodes were used throughout the test.

During the IITRI demonstration, a tracer test was performed to determine whether the contaminants were migrating outside the treatment zone. Halon 2402 was injected in a well nine feet from the western ground electrode array at a depth of seven feet. After the tracer was not detected at significant concentrations in the vapor stream after four hours, a second, higher dose of the tracer was injected. The tracer was detected in the vapor stream 104 minutes after the second injection. A detailed discussion of the tracer test is included in Section VIII.C in IITRI's Draft Final Report included as Appendix A.1.

6.3.2 The KAI Demonstration

Design

HNUS designed the SVE system for the KAI demonstration. This design was based on Equation (6-3), experience with typical SVE systems, and lessons learned during IITRI's demonstration. The ejectors used during IITRI's demonstration provided the extractive force. The design included eight vertical vapor extraction wells, two horizontal extraction wells, eight transducer wells (subsurface pressure monitoring wells), manifolds, and a vapor barrier. Drawings showing the layout and well construction details are included in Appendix B.3.

The extraction wells were designed so the wells could be used as extraction, passive, or injection wells. Three extraction wells were located on each side of the expected heated volume to allow vapors to be extracted from either or both sides or to pull vapors across the heated volume by using the wells on one side as extraction well and the wells on the other side as passive or injection wells. Since the middle of the volume would be heated first, two extraction wells were located in the middle of the heated zone to remove heated vapor during the early stages of the demonstration. HNUS decided to use 2-inch diameter extraction wells based on flow rate calculations. These flow rate calculations were made using a spreadsheet based on Equation (6-3). The spreadsheet shows the expected flow rate for a range of well diameters, permeabilities, and vacuums. An example of this spreadsheet is included in Appendix B.4. The horizontal extraction wells were included to provide a way to remove vapors near the surface. If air monitoring indicated increased concentrations of contaminated vapors at the surface, the horizontal wells could be used to remove the contaminated vapors. The transducer wells were installed to monitor pressure during vapor extraction testing and operations to estimate the radius of influence.

Installation

Extraction, transducer, field measurement, antenna, and horizontal wells were installed as shown in the drawings included in Appendix B.3. The extraction, transducer, and horizontal wells make up the SVE system. The installation of these wells is discussed below.

HNUS constructed the transducer wells using 1-inch diameter PVC pipe and drilled to create a screened section. Transducer wells 1 and 7 were installed in the same boreholes as transducer wells 2 and 8, respectively. Transducer wells 1 and 7 were screened from approximately 21 to 25 feet below the ground surface in a sand pack. The borehole was then filled with a 6-foot deep bentonite plug. Transducer wells 2 and 8 were screened from approximately 11 to 15 feet below the ground surface in a sand back. The remaining 8 feet of annulus was backfilled with bentonite. Transducer wells 3 through 6 were screened from approximately 10 to 14 feet below the ground surface in a sand pack. The remaining 11 feet were backfilled with bentonite.

HNUS constructed the 8 vertical extraction wells using 2-inch diameter fiberglass with holes drilled in the pattern shown in the well detail drawing included in Appendix B.3. All the extraction wells except wells 2 and 7 were screened from approximately 11 to 20 feet below the ground surface.

Extraction wells 2 and 7 were screened from approximately 3 to 12 feet below the ground surface. The extraction wells were backfilled with sand and plugged at the top with 3 feet of bentonite.

The horizontal extraction wells were constructed from two 4-foot long sections of 2-inch diameter fiberglass screened by drilling holes in the pipe. These sections of screened fiberglass were placed in shallow trenches (less than 2-feet deep) on each side of the treatment zone.

As shown in Drawing Number 3688G012, included in Appendix B.3, three manifolds connected the following groups of wells:

- Wells E1, E2, and E3
- Wells E4 and E5
- Wells E6, E7, and E8

These manifolds and the line from the horizontal wells were 2-inch fiberglass pipe. The line from the horizontal wells was also run along the eastern edge of the vapor barrier. These manifolds were connected to the header pipe using 2-inch hoses with quick-connect couplings. The hoses, couplings, and ball valves at the line to each extraction well allowed operation in several extraction configurations.

HNUS used plain polyethylene sheet as a vapor barrier during the February field test of the SVE system. This vapor barrier was replaced with a nylon-reinforced polyethylene sheet after the antenna sleeves were installed. Any tears during installation and places where the transducer, field measurement, and antennae wells extended through the vapor barrier were sealed with nylon-reinforced polyethylene tape.

SVE Testing

HNUS performed on SVE test, as described in the "Vapor Extraction Test Plan" included in Appendix B.3, during February 1994. During this test, the SVE system was operated at vacuums of 15, 20, and 25 inches H_2O at the ejectors. This test indicated that a vacuum higher than 20 inches H_2O (less that -20 inches H_2O pressure) would be necessary to affect the treatment area during the early stages of the KAI demonstration.

During the February SVE test, EPA SITE used transducers to measure the subsurface pressures. the extraction well configurations used during this test are presented in Table 6-2. The data reported by EPA SITE is included in Appendix B.3 and approaches the sensitivity limitations of the equipment. Therefore, this data is inconclusive and indicates that the tests should have been operated at a vacuum of approximately 40 inches H2O at the ejectors. The tests were operated at a 20 inches H2O at the ejectors so that the data collected by HNUS using Magnehelic gauges could be compared to the data from these test.

TABLE 6-2

EXTRACTION WELL CONFIGURATIONS FOR THE TRANSDUCER TESTS

HNUS Test No.	Vacuum at the Ejectors (inches H_2O)	Extraction Wells in Use
1	20	E4, E5
2	20	E1, E2, E3
3	20	E3
4	20	E2
5	20	E1

HNUS performed additional SVE tests during March and April 1994. These tests indicated that a vacuum at the ejectors of 40 inches H_2O would influence the treatment zone during the early stages of the KAI demonstration.

Operation

During the KAI demonstration, the SVE system was operated not to achieve a specific removal rate but to observe a variety of extraction patterns. HNUS hoped to learn which extraction configurations effectively covered the treatment zone by monitoring the subsurface pressure in the transducer wells and the vacuums in the extraction well lines. For inactive extraction wells the vacuum in the line represented subsurface pressure.

In order to learn about different configurations and to try to control the flow of contaminants from outside the treatment zone, HNUS operated the SVE system in the configurations and at the vacuums listed in Table 6-3.

TABLE 6-3

SUMMARY OF SVE OPERATING CONDITIONS

Operating Condition	Starting Date	Ending Date	Extraction Wells	Passive Wells	Vacuum at Ejectors (in. water)
1	4/21/94	5/9/94	E2, E4, E5	NA	40
2	5/9/94	5/12/94	E2, E3, E4, E5	NA	40
3	5/12/94	5/13/94	E2, E3, E4, E5	E8	40
4	5/13/94	5/16/94	E2, E3	E8	40
5	5/16/94	5/21/94	E2, E3, E5	E8	40
6	5/21/94	5/22/94	E5	E8	25
7	5/22/94	5/23/94	E1, E2, E3, E4, E5	E6, E7, E8	25
8	5/23/94	6/8/94	E4, E5	E1, E2, E3, E6, E7, E8	20
9	6/8/94	6/14/94	E4, E5	E1, E2, E3, E6, E7, E8	15
10	6/14/94	6/24/94	E1, E2, E3	E6, E7, E8	15

Generally, extraction took place from the middle of the heated zone. Wells E1, E2, and E3 were used to create a flow across the treatment zone from wells E6, E7, and E8.

HNUS tried to operate the SVE system so contamination would not be drawn into the treatment zone. Therefore, the vacuum was reduced when vacuums of 0.5 inches H_2O were measured in the outer transducer wells. If measurable positive pressures had been detected in the horizontal wells or contaminant concentrations around the vapor barrier had increased, the horizontal extraction wells would have been put on line. The subsurface pressures, the compressed air, flow rate for the inlet to the ejectors, the mixed vapor flow, the pressure of the suction and discharge lines, and the temperature of the vapor and mixed vapor stream were monitored twice a day. The collection and analysis of vapor stream samples are discussed in Section 7.

The radius of influence was estimated at different times during the demonstration using subsurface pressure contour maps. These maps were based on the subsurface pressure readings. The change in permeability was estimated using these radii of influence, the flow rates estimated by Radian Corporation, and equation 6-3. The permeability increased by approximately an order of magnitude. These calculations and the contour maps are included in Appendix B.4.

6.4 LESSONS LEARNED AT SITE S-1

During these demonstrations many lessons were learned about integrating the RFH and SVE systems. Some of the lessons learned during the IITRI demonstration were taken into account when designing and operating the KAI system. The lessons learned from these demonstrations are discussed below. Conclusions and recommendations are included in Section 9.

6.4.1 The IITRI Demonstration

The SVE system used during the IITRI demonstration was designed based on the assumption that the heated vapors would be forced toward the ground electrodes and to the surface. Therefore, IITRI's SVE system relied on the ground electrodes and the horizontal wells at the surface to remove the contaminated vapors. This system used low vacuums to remove high air flows. A better approach would be to design the SVE system using standard engineering practices while considering the limitations and requirements of the heating system. Using standard engineering practices would change IITRI's SVE system in the following ways:

- Only a few ground electrodes would be used as extraction wells.
- A higher vacuum would be used initially and decreased later.
- Subsurface pressures would be monitored inside and outside the heated volume.
- Extraction patterns would be changed periodically to reduce the impact of preferential pathways.
- The horizontal wells would only be used if contaminated vapors collected beneath the vapor barrier.

Monitoring subsurface pressures may not provide conclusive data on the migration of contaminated vapor but will allow the volume influenced by the SVE system to be estimated. Monitoring wells should be located both inside and outside the heated volume.

6.4.2 The KAI Demonstration

Measurements made during the demonstration show that the radius of influence of the extraction wells and the flow rate through the heated zone can be controlled by adjusting the vacuum. If the vacuum is decreased, the radius of influence of that well and the flow rate from that well will decrease. The flow rate will respond to changes in the vacuum more than the radius of influence.

Extracting from the middle of the heated volume appeared to be more effective than extracting from the edges of the heated volume. However, the most effective extraction location will be dependent on site-specific characteristics and the objectives of the project.

Fewer wells could have been used to influence the same heating volume. The number of subsurface pressure monitoring wells could have been drastically reduced because extraction wells that are inactive or in use as passive wells can be used to monitor the subsurface pressures.

6.4.3 Both Demonstrations

The well casings must be nonconductive material capable of withstanding the expected maximum temperature of the heated volume. This material must also be noncorrosive if the surrounding soil or the vapor stream is expected to be corrosive.

Ejectors are well suited for use in the explosive and/or corrosive environments.

Selection of instrumentation devices such as flow meters may be difficult due to the range of temperatures, moisture contents, and contaminant concentrations expected in the vapor stream. The expected vapor stream temperatures will be less than the expected soil temperatures.

Horizontal wells should only be used during the following situations:

- when the treatment zone is shallow,
- when the contaminated volume is not accessible from the surface directly above the contaminated soil, and
- when vertical extraction wells fail to prevent contaminated vapors from collect beneath the vapor barrier.

For shallow treatment volumes and cases when vertical extraction wells fail to prevent migration of contaminants to the surface, the horizontal wells should be buried in shallow trenches.

7.0 CHEMICAL AND PHYSICAL DATA

7.1 INTRODUCTION

Results of the IITRI and KAI demonstrations are evaluated from data collected before, during, and after RFH system operation. Data was collected to define pre- and post-demonstration soil (Appendix A.3 and B.5) and pre-, during, and post-demonstration vapor stream physical and chemical characteristics (Appendices A.5, A.7, B.4, and B.6), treatment volume temperatures (Appendices A.1 and B.1), and electrical use and efficiencies (Appendices A.1 and B.1).

7.2 SOIL

HNUS collected pre- and post-demonstration soil samples for both the IITRI and KAI demonstrations. EPA/SITE provided analyses for volatile organic compounds (VOCs), semivolatile organic compounds (SVOCs), and total recoverable petroleum hydrocarbons (TRPH) through the Radian laboratory in Austin, Texas. In addition, EPA/SITE provided moisture and sieve analyses of the soil for physical classification.

Soil samples were collected from three soil horizons (7, 12, and 17 feet deep) and analyzed to determine the type and numbers of microorganisms present.

IITRI performed a tracer test to confirm that vapors were drawn into the heated volume. A small amount of Halon® was injected into subsurface soils outside the heated soil volume and detected in the SVE system. Inward movement of the Halon® confirmed that the SVE system collected heated vapors for treatment as planned.

7.2.1 Sampling Strategy

The primary objective of a sampling strategy for the RFH demonstrations was to collect samples that would accurately and precisely characterize the chemical properties of the soil. The recommended procedure for achieving acceptable sampling accuracy and precision, recommended in Test Methods for Evaluating Solid Waste, SW-846 (US EPA, 1986), was followed.

Sampling accuracy is normally achieved by using a three-dimensional random sampling strategy. An imaginary three-dimensional grid of sampling points is established in the soil and a random number generator is used to select points to be sampled. Sampling precision is achieved by taking an appropriate number of samples from the population. The appropriate number of samples is the least number of samples required to generate a precise estimate of the true mean concentration of the chemical contaminants.

A confidence interval (CI) of 80 percent, based on a paired t-test, was selected for evaluating the soils at Site S-1. The values of a normally distributed contaminant that are outside the limits of an 80 percent CI are equally distributed between the left (lower) and right (upper) tails of the normal curve. Since only the upper portion of the curve is of interest, the CI employed to evaluate solid wastes is, for all practical purposes, a 90 percent interval.

A statistical analysis of contaminant concentrations representative of the southeast corner of the Site S-1 sump area indicated that 48 samples would ensure accurate characterization of the site contaminants. Demonstration activities included collecting 48 soil samples before (pre-) and 37 after (post) the IITRI demonstration to assure an adequate data base. Nine samples were taken from the saturated zone (below 24 feet) during the predemonstration sampling, but were not repeated during the post demonstration sampling. Soil samples from the saturated zone were used to characterize the volume under the heated zone. Samples were not obtained from two sampling intervals EB02-0812 and EB02-1214 due to poor recovery.

The final sampling strategy required slight modifications. To minimize drilling costs, most soil samples were collected from the bores required for IITRI's electrodes. That biased sampling pattern somewhat toward the centerline and sides of the heated zone. This small reduction in sampling accuracy was offset by the number of samples collected.

The sampling strategy for the KAI demonstration was similar in most respects. Fewer samples were collected near the water table because the estimated heating time was insufficient to heat the deeper soils. As in the IITRI demonstration, the sampling locations were positioned to utilize the borings needed for antenna sleeves, extraction wells, and monitoring equipment.

The soil samples were collected by placing four 6-inch long, stainless steel liners in a 2-foot long split spoon and advancing the spoon to the target depth. The second liner from the bottom was retained for analysis. When duplicate samples were required, the third liner was retained. The site geologist covered the ends of each liner with Teflon® tape and capped the liners with polyethylene caps to prevent the loss of volatile compounds. Site personnel used the following procedure to decontaminate the liners and spoons:

- thoroughly scrub with Alconox detergent,
- rinse with potable water,
- rinse with pesticide-grade methanol,
- rinse again with ASTM Type II water, and
- place on a clean surface to air dry.

The liners and spoons were then wrapped in aluminum foil for storage. EPA personnel observed decontamination, drilling, and sample preparation activities to assure proper handling.

EPA provided analytical services through the agency's SITE Program. HNUS personnel collected and labeled samples, prepared Chain-of-Custody forms, and surrendered the samples to Science Applications International Corporation (SAIC) personnel for transport to the laboratory. The Radian Corporation laboratory in Austin, Texas, performed the analyses and reported the results to SAIC. SAIC chemists reviewed the data and reported the results to HNUS. EPA methods were used for the soil analyses (Table 7.1).

TABLE 7-1

EXTRACTION AND ANALYTICAL METHODS FOR SOIL ANALYSES

PARAMETERS	EXTRACTION METHOD*	ANALYTICAL METHOD
VOC	Method	8240
SVOC	3540	8270
TRPH	Method	418.1

*"Method" indicates that the extraction method is defined as part of the analytical method. See SW-846 for details about the procedures.

EPA's VOC, SVOC, and TRPH data are presented in this section and the Appendices. Additional TPH data are presented in IITRI's final report (see Appendix A.1).

7.2.2 Results

Evaluation of analytical data from the soil samples proved to be difficult. Some contaminants occurred at very low concentrations (near detection limits). The laboratory diluted some samples to accurately measure a few compounds occurring at higher concentrations, so other compounds were reported below the resulting, higher detection limits. The HNUS laboratories have observed matrix interferences in many Kelly AFB soil analyses, and Radian may have had similar difficulties. Several compounds, including acetone, 2-butanone, methylene chloride, and some solvents and fuel fractions were reported in trip blanks. Some, but not all, of the compounds reported in trip blanks are common laboratory contaminants. Reports from SAIC stated that the data had been validated and no data qualifiers were required. At a minimum, the concentrations reported for compounds detected in trip blanks are suspect. The data are not suitable for the statistical analysis originally planned, but do offer insights into contaminant movement during soil heating.

Radian laboratory personnel are reported to have removed gravel from some samples collected during the IITRI and KAI demonstrations prior to analysis. None of the following data were reported:

- sample numbers of the screened samples (if any),
- screening criteria (gravel size, etc.),
- matrix sampled, and
- weight or volume of the removed gravel.

Reported concentrations in such cases are representative of the selected material, not the entire sample matrix.

Site operations may have caused other artifacts in the soil data. HNUS changed SVE operations several times during the KAI demonstration to observe the effects of vacuum changes and changing soil permeabilities. The changes were a necessary part of planning for a full-scale demonstration, but they resulted in less than optimum vapor removal. HNUS dewatered the lower portion of the soil heated by IITRI to heat as deeply as possible and prevent electrical shorting at the electrode tips. The dewatering may have resulted in groundwater contaminants being swept into the heated soil and the SVE system. The locations selected for the demonstrations were within a larger area of documented contamination. In both demonstrations, the SVE system drew air from the surrounding contaminated soils, because the heated zones were covered with impermeable vapor barriers. The effects of soil cooling after RFH cannot be quantified with existing data. These operational variables were anticipated and can be mitigated in a full-scale operation.

The non-homogeneous distributions of site contaminants prevent a meaningful statistical analysis of some soil data. Some of the data are characterized by fairly consistent concentration distributions interrupted by single detections at least two orders of magnitude greater than the mean. The patterns are typical of the centers of sites at which a few, small "hot spots" exist, and the concentrations do not appear in normal or log-normal distributions. Such data fail "goodness of fit" tests, and the mean concentrations must be evaluated with caution.

Broad patterns emerge in the data in spite of these and other difficulties. Arithmetic means are presented for simplicity. The discussions below focus on the following patterns:

- A few compounds, such as benzene, chlorobenzene, bis-2(ethylhexyl)phthalate, and pyrene, exhibited consistent movement through both the soil and SVE system. Both volatile and semivolatile compounds are represented.

- TRPH and TPH concentrations decreased significantly in the heated soil (similar decreases were measured by two different analytical methods during the IITRI demonstration).

- A comparison of concentrations in heated soils versus those in lower, cooler soils shows the beneficial effects of heating.

7.2.2.1 IITRI Demonstration

A report prepared by IITRI, enclosed in Appendix A.1, describes all phases of their operations, including the routine measurements recorded manually and by a data logger. Heating began on April 3, 1993, and soil temperatures near the center electrodes reached 150° C by April 19, 1993. Some soil volumes reached temperatures exceeding 900° C by May 20, 1993. The higher temperature measurements are probably inaccurate because temperatures exceeded the working limit of the thermocouples (899° C). The temperatures did exceed the melting point of the copper excitor electrodes (1083° C), as documented during the post-demonstration drilling.

Appendix A.3 contains the pre- and post-demonstration analytical results from the IITRI demonstration. Examples are discussed below in greater detail. The geometry of the heated soil volume and the extraction of heated vapors through the ground electrodes led to data aberrations in addition to those described above. Cool, contaminated vapors moved from soil and groundwater outside the heated volume to the electrodes. Overall removal was less effective in the corners and bottom of the rectangular volume.

Volatile Organic Compounds

The analytical data for volatile organics in the soil samples illustrates the problems encountered in evaluating the data. The following table shows the percent removal for chlorobenzene based on pre- and post-demonstration sample pairs from the heated volume:

TABLE 7-2

CHLOROBENZENE CONCENTRATIONS IN SOIL SAMPLES (PPB)
IITRI DEMONSTRATION

SAMPLE GROUP	INITIAL MEAN CONCENTRATION	FINAL MEAN CONCENTRATION	PERCENT REMOVAL
ALL SAMPLES	4,117	4,856	-18
0' TO 18' DEEP	162	791	-388
18' TO 24' DEEP	15,543	16,598	-7

The eight concentrations reported as detection limits indicate that the detection limits were low. Two explanations for the reported increases may be suggested, but neither can be confirmed. First, more complex compounds might have been destroyed, leaving chlorobenzene as a by-product. A second, more likely explanation is that the SVE system drew chlorobenzene into the edges of the heated volume from the surrounding soils and the contaminated groundwater beneath the site (which had concentrations of 12,000 to 25,000 ppb).

Observed acetone concentrations are more puzzling. The means of all pre- and post-demonstration samples indicate an increase of 1,061 percent, with an increase of 2,601 percent in soils above a depth of 18 feet. One sample pair indicated an increase of 7000 percent in soil that was heated to several hundred degrees Celsius (acetone boils at 56.2° C). Only six of the 27 concentrations reported as below detection limits are less than the practical quantitation limit (PQL) of 100 ppb. Four of those 27 concentrations exceed the PQL by more than an order of magnitude. Low concentrations of acetone and other common lab contaminants were detected in some trip blanks. These and similar considerations preclude any meaningful evaluation of these highly volatile compounds.

The difficulties involved in evaluating the VOC data for soil samples may be summarized as follows:

- Some sample results are reported as below elevated detection limits.
- Some VOC concentrations reported far exceed any reported during a RI conducted at Site S-1.

- Some high concentrations near the ground electrodes may be the result of vapors from surrounding soils or contaminated groundwater condensing near the electrodes during cooldown.

- High temperatures near the excitor electrodes may have destroyed some compounds, leaving increased concentrations of lighter compounds. However, it is unlikely that acetone remained in soils at temperatures that melted copper.

Such problems led investigators to perform more precise vapor sampling during the second (KAI) demonstration.

Semivolatile Organic Compounds

Removal of SVOCs is especially important in an evaluation of heating-assisted SVE. Compounds with very low vapor pressures are difficult to remove by SVE at ambient ground temperatures. The following table shows the percent removal for three SVOCs based on pre- and post-demonstration sample pairs from the heated volume:

TABLE 7-3

COMPOUND CHARACTERISTICS
IITRI DEMONSTRATION

COMPOUND	CARBON ATOMS	MOLECULAR WEIGHT	SAMPLE DEPTH (feet)	PERCENT REMOVAL*
Bis(2-ethylhexyl)phthalate	24	390.57	All Samples	37
			0-18	64
			18-22	22
Pyrene	16	202.26	All Samples	68
			0-18	87
			18-22	-52
Benzo(a)anthracene	18	228.30	All Samples	25
			0-18	65
			18-22	-281

*See Appendix A.3 for details.

Results indicate the mobilization/removal of bis(2-ethylhexyl)phthalate (a liquid at ambient ground temperatures), pyrene, and benzo(a)anthracene (solids at ambient ground temperatures). The poor removal efficiencies at depths below 18 feet suggest that vapors moved downward to cooler soils or moved up from soils in the saturated zone. In either case, additional attention is required to assure adequate SVE at those depths.

Total Recoverable Petroleum Hydrocarbons

The means of all TRPH pre- and post-demonstration sample results indicate a removal of 22 percent during the demonstration. The removal efficiency is 50 percent for samples above a depth of 18 feet and -14 percent for samples below that depth.

Seven sample pairs from the four excitor borings indicate a removal of 94 percent. Four of the seven post-demonstration results were below detection limits (<25 to 28 ppb). Seven samples is a small population that represents a small portion of the total volume, but the results are encouraging.

Total Petroleum Hydrocarbons

For consistency with past laboratory and field efforts, IITRI performed in-house TPH analyses for diesel range organics (DRO) using the California DHS method. The California method is a modification of EPA Method 8015 that employs a gas chromatograph and flame ionization detector, whereas Method 418.1 employs infrared spectroscopy. Either may be calibrated to the diesel range (C_{10}-C_{28}) of organic compounds. Some researchers have reported that Method 418.1 consistently overestimates TPH concentrations if soils contain natural fatty materials (e.g., cedar wax or pine resin). However, IITRI's results compared favorably with results reported by Radian during this demonstration. Appendix A.1 (Section VII B) contains additional details about the IITRI analyses.

An average of all samples indicated a TPH decrease of about 53 percent, while samples collected above a depth of 20 feet showed a decrease of about 63 percent. These results are consistent with the knowledge that initial TPH concentrations generally increased with depth and the deeper, more moist soils are more difficult to heat.

Moisture

IITRI reported soil moisture measurements for both pre- and post-demonstration samples (see Appendix A.1, Section VII-B). Pre-demonstration results ranged from about 9 to 26 percent moisture, with most samples in the 18 to 21 percent range. Most of the samples exhibiting low soil moisture were from 20 to 22 feet below grade. That elevation is near the water table, but a few feet above the dense, underlying Navarro clay. Boring logs indicate a greater gravel content below a depth of about 20 feet, which may explain the lower soil moisture.

Classification

Grain size analyses were performed for the pre-demonstration samples. The full report is enclosed as Appendix A.5. Results are presented as the percent of gravel, sand, and fines (silt and clay) in each sample. The analyses confirm that greater quantities of gravel lie below a depth of 18 to 20 feet. Gravel comprised less than 30 percent of most samples above that interval and greater than 60 percent of samples below that interval. A single sample from the underlying Navarro Clay was 75 percent silt and clay and included colloidal material.

Temperature

The temperature patterns observed during the soil heating and cooldown are presented in Appendix A.1. The heating progress may be summarized as follows:

- Soil heating began near the surface, at the center of the heated volume. Soil heating then proceeded outward and downward, as IITRI predicted.

- Near-surface soils in the center of the heated volume reached the target temperature of 150° C in less than two weeks. This zone eventually reached a temperature of several hundred degrees, and heating was stopped when underground arcing seemed to occur. Portions of the copper excitor electrodes melted.

- Temperatures near the ground rows of electrodes rarely exceeded 100° C. The SVE system drew cooler vapor from surrounding soil to those zones, and unusually heavy rainfall probably kept the soil moisture high.

IITRI turned the RF source off periodically for service or to allow site personnel to make measurements under the RF shield structure. Continuous monitoring indicated that the heat loss was less than expected during such periods. Often, the temperature distribution patterns improved significantly after such a break. Schedule pressures dictated almost continuous full-power operation, but these observations suggest that an intermittent mode of operation might result in more uniform heating.

Tracer Test

IITRI conducted tracer tests on May 30, 1993, to document movement of soil vapors from outside the heated soil volume toward the SVE system. A small quantity (about 5 ml) of Halon® 2402 was injected into soils about seven feet below grade at a point about nine feet from the western edge of the electrode array. Low detected concentrations led to a second test in which about 25 ml were injected. A strong detection was obtained, showing the desired movement of soil vapors toward the SVE system. No further tests were conducted because using greater quantities of Halon® raised environmental concerns. Additional details are provided in the IITRI report (Appendix A.1).

7.2.2.2 KAI Demonstration

Volatile Organic Compounds

Chlorobenzene was detected most frequently. As the Tables in Appendix B.5 show, removal rates were highly dependent on the depth and position in the heated soil volume. This pattern was not unexpected; KAI did not have sufficient time to heat the entire volume. Samples below 17 feet deep show a removal rate of -24 percent (a marked increase). This result is consistent with observations from the IITRI demonstration and indicates that the removal of heavy vapors from the lower gravely soil requires additional attention. The removal rate for all sample pairs is also -24 percent, reflecting the lack of deep heating and, again, operation of the SVE system. Removal rates for other sample groups range from -76 percent to 62 percent. As with the IITRI demonstration, data evaluation requires caution because:

- Soil contamination at the site is highly heterogeneous.
- Some detection limits are very high.

As a result, soil VOC data are of little use in an evaluation. Vapor analyses probably provide a more reliable record of contaminant movement for the KAI demonstration.

Semivolatile Organic Compounds

The analytical results for bis(2-ethylhexyl)phthalate and pyrene are also somewhat confusing, but offer insight into the effects of heating. The removal rates for these compounds, based on all samples, are 6 percent for bis(2-ethylhexyl)phthalate and 50 percent for pyrene. As tables in Appendix B.5 show, different volumes exhibit a wide range of change. The most important point, is that these compounds are difficult to impossible to mobilize with conventional SVE because they have low vapor pressures and Henry's Law constants.

Total Recoverable Petroleum Hydrocarbons

Tables in Appendix B.5 show the TRPH removal rates for several sample combinations. Rates ranged from -7 percent (all samples) to 36 percent for samples above a depth of 17 feet. The variables in the heating process were discussed above. Considering the brief heating in a small volume, TRPH removal compares favorably with results from the IITRI demonstration.

Moisture

Radian analytical reports indicate that soil moisture varied little from that observed during the IITRI demonstration. Soils above a depth of 18 to 20 feet exhibited moisture contents of about 20 percent and the moisture content of deeper soils was typically 8 to 10 percent.

Classification

Soil classification measurements were not repeated for the second demonstration. Boring logs for the IITRI and KAI demonstrations indicate that the lithologies were similar, with a substantial increase in gravel content below a depth of 18 to 20 feet. Also, the logs indicate the capillary fringe starts between 18 feet and 20 feet.

Temperature

The total energies delivered during the IITRI and KAI demonstrations are not directly comparable for two reasons. First, unexpected delays in receiving permission for KAI to operate delayed the start of full-power operations by nearly three weeks. Second, the original budget limited heating time and did not permit delivery of an equivalent amount of RF energy to the soil. As discussed in Sections 5 and 8, RFH system operation and cost have a low sensitivity to electrical power efficiency.

The temperature patterns observed during the soil heating and cooldown are presented in Appendix B.1. The heating progress may be summarized as follows:

KAI began by using an antenna (A1) in the southernmost antenna well. The goal was to begin heating at depths of about 10 to 14 feet, then move downward and periodically switch operation to the northernmost antenna (A2). Given time to switch antennas and move them vertically, the volume heated should have been approximately equal to that heated by IITRI.

The shorter, revised schedule was interrupted by two minor malfunctions:

- The nitrogen purge line to antenna A1 developed a small leak at the beginning of a three-day, holiday weekend. Under normal circumstances, KAI could get prompt delivery of additional nitrogen. However, none was available during the weekend and a small electrical short damaged the inner coaxial conductor.

- A spare inner conductor was damaged in transport to the site. The repair was simple, but added a brief delay to the project.

KAI delivered the most energy to antenna A1, with sufficient operation of antenna A2 to demonstrate that switching would not require substantial returning. Most of the operations with antenna A1 were at a single depth, and antenna switching proceeded very smoothly.

7.3 VAPOR

7.3.1 IITRI Demonstration

A knowledge of vapor stream properties is important in order to identify process changes critical to system operation. During the IITRI demonstration, temperature, pressure, flow, and chemical composition, and concentration were monitored. Temperature, pressure, and flow data are presented in Appendices B.4 and B.6 and discussed in Section 6.

Procedure

Extracted soil vapors were sampled and analyzed for total petroleum hydrocarbons, VOC's, and SVOC's. The primary purpose was to monitor the release of petroleum hydrocarbons and chlorinated compounds in compliance with the Texas Air Control Board's (TACB) standard exemptions 68, 80, and 118 according to Section 382.057 of the Texas Clean Air Act. Permit exemption No. BG-0108-F was applied for by Kelly AFB ERMO and received on June 25, 1992.

A secondary purpose for the vapor analysis program was to document and develop a reliable, cost efficient method for monitoring emissions and tracking operation effectiveness. Lessons learned during the IITRI demonstration were used to improve the procedures and methods used in the KAI demonstration (see Section 9 for details).

These standard exemptions specify discharge limits and operational criteria, as follows:

- total emissions of petroleum hydrocarbons of less than 1 pound per hour (lb/hr),
- total emissions of chlorinated compounds of less than 24 ppm,
- the discharge must be burnt in a flare,
- the tip velocity must be less than 60 ft/sec, and
- the burn is smokeless.

The required QA level and resulting cost for vapor analysis was purposely lowered to allow frequent collection and analyses. These analyses were originally conceived as a screening tool for operation, but several problems encountered during field implementation prevented this use. However, the results did yield several interesting conclusions.

Extracted soil vapor samples were collected from a sampling port on the vacuum line, upstream of the ejector assembly. A peristaltic pump pulled vapor from the vacuum line through a sampling train consisting of a flask to remove any solids and liquid and a sample vial filled with carbon for VOCs and TPH (NIOSH 1003) or XAD_2 resin for SVOCs (NIOSH 5504). One quarter-inch diameter, silicone tubing was used to connect the assembly. Detection limits were a function of the volume of air pulled through the sampling tubes. Fluctuations in humidity required adjustments in volume based on laboratory results and recommendations. One to ten liters of vapor were pulled through the sample tubes.

VOCs, SVOCs, and TPH were analyzed by EPA methods SW 8010 and 8020, Modified TO-13, and SW 8015, respectively. Level II quality control was achieved by calibration at five (5) point intervals and surrogate recovery analyses. Surrogate data are attached in Appendix B.6.

Several problems and potential solutions were identified during vapor sample collection and evaluation. First, the XAD_2 resin will not adsorb most light SVOCs at elevated temperatures ($>68^{\circ}F$). Second, analysis by GC instead of GC/MS restricts the types of compounds reported. Third, quantitative results will require the performance of regular spike analyses and increased costs.

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Results

As a qualitative screening, vapor stream analyses detected many compounds previously identified during soil sampling (see Appendix A.7). Even at maximum concentrations, air emissions were well below the regulatory limits.

Two distinct trends are readily identified by examination of the data. First, the data show many detections at relatively high concentrations followed by a period of few, low-concentration detections, followed again by a marked increase in detections and concentrations. Second, concentration swings are numerous and large.

7.3.2 KAI Demonstration

7.3.2.1 Screening Data

As with the IITRI demonstration relatively frequent, inexpensive characterization of the vapor stream was performed. Observed contaminant flows were well under the requirements of the flare operating permit exemption.

7.3.2.2 Radian

EPA/SAIC selected Radian Corporation to conduct more sophisticated vapor sampling and analysis. Radian's report is included as Appendix B.6. VOC grab samples were collected directly in SUMMA® stainless steel canisters, while SVOC samples were collected over a four-hour period. SVOC sampling employed a modification of the EPA Method 0010. Since the vapor line was only two inches in diameter and the vapors were already heated, Radian omitted the heated probe normally used for gas sampling. Samples flowed directly to a condenser and a XAD-2 resin cartridge. The control console that monitored flow rate and volume was located downstream of the condenser and cartridge.

The results may be summarized as follows:

- An average SVE flow rate of 30 to 80 cubic feet per minute was maintained.
- Approximately 90 to 120 pounds of VOCs were extracted (removed), including 15 to 20 pounds of chlorobenzene.
- Approximately 5 to 10 pounds of SVOCs were removed, mostly isomers of dichlorobenzene.

7.4 WATER

Site S-1 lies over a contaminated shallow aquifer and contamination in soil moisture above over the aquifer probably reflects soil contamination patterns. The demonstrations created two volumes of contaminated water above ground:

- The aquifer beneath the soil heated by IITRI was continuously dewatered. Water was stored in tanks on the site and periodically delivered to the Kelly AFB EPCF for treatment. No dewatering occurred during the KAI demonstration.

- HNUS kept about 100 gallons of water in a seal pot at the flare to prevent a flashback from the flare through the SVE system. The quantity of water gradually increased while soils dried out, and smaller quantities of water from the seal pot were also delivered to the EPCF. Concentrations of heavier compounds were expected to increase, while the more volatile compounds moved through the flare to be burned.

HNUS coordinated deliveries of water with EPCF personnel to assure that the additional water did not violate flow or chemical concentration provisions of the plant's discharge permit.

7.4.1 Groundwater

EPA's SITE activities included the sampling and analysis of groundwater from three existing wells at Site S-1. Temporary monitoring wells S1-TW09, S1-TW10, and S1-TW11 were sampled (see Appendix F). EPA identified the wells as KRF-09-GW118, KRF-10-GW114, and KRF-DW02-GW119, respectively. VOC and SVOC detections included chlorobenzene (12,000 to 25,500 ppb), benzene (596 and 782 ppb), dichlorobenzene (up to 11,000 ppb), and naphthalene (71 to 121 ppb). Bis(2-ehtelhexyl)phthalate was detected in one sample at 218 ppb.

7.4.2 Dewatering Effluent

EPCF personnel subjected samples to the routine tests required for treatment and discharge before accepting the dewatering effluent. The lab used Methods 8020 and 8070 for the analyses and the results are presented in Appendix A.9. Concentrations of benzene, chlorobenzene, and dichlorobenzene exceeded 1000 ppb. SVOC analyses confirmed the presence of dichlorobenzene, but most other SVOC concentrations were below detection limits. The detection limits for SVOCs were high, typically 660 to 3300 ppb. The chemical concentrations posed no problems, so the main task for delivering effluent consisted of estimating and coordinating flows. Once communications were established, effluent disposal posed no problems.

7.4.3 Seal Pot

The flare incorporated at seal pot partially filled with potable water to prevent backflash. The water in the seal pot was sampled and analyzed before the overflow was delivered to the EPCF (Appendix A.10). VOC, SVOC, and TPH analyses were performed. Concentrations were low, but the presence of bis(2-ethylhexyl)phthalate (95 ppb) was of particular interest.

7.5 HEALTH AND SAFETY AIR QUALITY MONITORING

HNUS conducted routine air monitoring to assure the safety of site workers and to be certain that the VES collected organic vapors for treatment. The company's experience from performing a RI at the site indicated that the site posed little or no risk to workers performing routine tasks if site soils were undisturbed. An increase in measurable vapor concentrations was noted during previous drilling operations, with concentrations generally increasing with increased drilling depth. The site is flat, open on all sides, and usually breezy, so vapors dispersed quickly. IITRI's quonset-shaped RF shield presented the most likely location for vapor buildup, and it was fitted with a blower that moved a constant flow of air through the structure. The blower output exhausted through activated carbon drums.

7.5.1 Procedure

Site personnel used three types of instruments: photoionization detectors, flame ionization detectors, and combination devices that measure the explosive properties and oxygen content of vapors. The HNu model PI-101 is typical of the photoionization devices used. The device is simple to calibrate and use, but required frequent repairs that cannot be readily performed in the field. The Foxboro OVA 128, a flame ionization instrument, requires a hydrogen supply and is somewhat more complicated to use. However, it provided very reliable service and was used most frequently during the tests. The MSA 360 LEL/O_2 monitors the lower explosive limit, oxygen content, and carbon monoxide content of air. The OVA served as the main survey instrument. It was used frequently to monitor working areas and determine if use of the other instruments was warranted. All three devices were used during drilling to monitor soil and borehole vapors. The LEL/O_2 was used periodically to check the air beneath the IITRI RF shield and near the propane tanks and flare. No explosive situations or oxygen deficiencies were noted.

7.5.2 Results

Background vapor concentrations, as determined from measurements near the upwind site boundary, were typically 0 to 3 ppm, with occasional excursions to 8 or 9 ppm. Several factors contributed to background changes. Moderate to strong breezes swept the site nearly every day, then diminished at night. This diurnal effect was less noticeable during cold weather, when winds were more constant. Winds from the West or Southwest often carried vapors from automobiles or aircraft during periods of heavy traffic. Southeast winds carried vapors from fuel transfer and flare operations at the adjacent fuel farm. Daily monitoring confirmed the effects of base operations; concentrations generally diminished on weekends, when the level of activity was low.

The greatest vapor concentrations were observed during drilling and soil sampling. Measurements made in a borehole or directly at a contaminated point on a sample occasionally indicated concentrations exceeding 1000 ppm. Samples nearest the water table exhibited the greatest concentrations. Breathing zone concentrations rarely exceeded background because of the breezes and the open nature of the site.

HNUS personnel checked vapors near the seal pot and storage (frac) tank as part of the daily health and safety checks. Detections exceeding 1000 ppm were occasionally observed in the tops of the storage tanks, but no increase in breathing or working zones was noted. The flare operated without noticeable odor.

IITRI personnel periodically entered their RF shield structure to measure the output of thermocouples in their electrodes. HNUS monitored vapors inside the structure before each entry at the structure's vents and doors. Vapor concentrations rarely exceeded background, but workers wore full-face respirators and worked in pairs for safety.

HNUS also monitored air beneath the vapor barrier used during the KAI test by placing the OVA probe tip under the barrier at several points around its periphery. No detections above background were observed, indicating that soil vapors moved to SVE wells, not to the soil surface.

Toxic characteristic leaching procedure (TCLP) analysis was performed on the activated oarbon used in the IITRI demonstration (see Appendix A.11). No compounds exceeded detection limits.

7.6 LESSONS LEARNED

The quality of soil data is inadequate for a statistical analysis of the demonstrations. That is due in part to occasional elevated detections that required sample dilution. Dilution, in turn, elevated the detection limits. This pattern can be overcome in an actual remedial action by focusing analyses on a few critical compounds. Other deficiencies resulted from the unexplained appearance of volatile contaminants in trip and field blanks. Some of the compounds observed in blanks appear to exist in site soils, but the quantitation remains suspect. Heavy SVOC compounds were mobilized and extracted, but the dynamics were not well defined.

Sampling near the sides of the heated volumes probably influenced the soil data greatly. The sampling pattern resulted in analysis of soils at points where contaminants were drawn from surrounding soils.

Routine vapor screening results were poor. An on-site gas chromatograph would assist site personnel in day-to-day operations. Plotting a few critical compounds would help in optimizing SVE system controls.

The SVE system drew vapors from soils surrounding the heated volume as well as vapors from heated soils. Some vapors may have condensed near the sides of the heated volume, skewing both soil and vapor analyses. The inherent effect cannot be avoided when a demonstration is conducted in a small portion of a much larger contaminated volume. The effect could be eliminated in a full-scale remediation by progressively heating from one side of the contaminated zone to the other or from the center to the edges.

8.0 CONCEPTUAL DESIGN AND OPERATION MODEL

8.1 INTRODUCTION

The following narrative presents conceptual plans for the planning and implementation of Phase II at Kelly AFB IRP Site S-1. Phase II is to include the complete planning and implementation of a full-scale demonstration of RF soil decontamination. For the propose of comparison, two RFH/SVE systems, IITRI and KAI, will be modeled. Design and operational plans, equipment lists, costs, and schedules for implementation of the demonstration systems are provided. The conceptual plans are based on conclusions reached in the evaluation of data generated in the Preplanning Phase and Phase I (see Sections 4 - Geology, 5 - Radio Frequency Soil Heating, and 6 - Soil Vapor Extraction and Treatment).

8.1.1 Basis For Action

A Remedial Investigation and Feasibility Study (RI/FS) are usually prepared prior to a remedial action under CERCLA. The RI defines the nature and extent of site contamination, identifies site-specific ARARs, and develops baseline risk assessments. If the results of the RI indicate that a remedial action is required, an FS is prepared. The FS develops and screens remedial alternatives and analyzes those alternatives in detail. In the case of an emergency or priority situation, a Focused Feasibility Study (FFS) can be prepared to facilitate a timely interim remedy. The FS and FFS are based on information gathered for the RI. The RI/FS is then used to recommend an action to remediate the site.

A commercial scale RFH/SVE demonstration requires two assumptions that would normally be dictated by the conclusions and recommendations of a FS or FFS. First, the nature and extent of contamination and resulting risk assessments require action and, second, RFH enhanced soil vapor extraction is the recommended alternative for soils treatment.

8.1.2 Demonstration Goals

The goals of the proposed demonstrations will be to broaden and validate commercial development of a RFH/SVE system while removing volatile and semi-volatile organic compounds from the soil matrices. The demonstrations must satisfy all environmental and human health standards and regulations while meeting these goals. The actual demonstration will be performed using the procedure required for a CERCLA remedial action as guidance. Modifications allowing for the development and research aspects of the demonstrations will be made as appropriate and in cooperation with the Texas Natural Resources Conservation Commission (TNRCC).

8.1.3 Site S-1

Site S-1 served as an intermediate storage and transfer area for wastes to be reclaimed off-base. The site was dominated by a sump which was later filled in with materials from various locations on base. The wastes included mixed solvents and petroleum, oils, and lubricants (POL). Inadvertent spills during this operation resulted in soil contamination. The RI for Site S-1 was completed in October 1994 and a contract for the design and construction of an interim groundwater extraction and treatment system based on an FFS is nearing field implementation. The purpose of the system is to prevent off-base migration of a plume of contaminated groundwater. See Section 4 for a complete site description and additional site characterization data gathered during Phase I. Additional site characterization information is contained in the RI report (HNUS, 1994).

A major consideration in the actual performance of these conceptualized demonstrations is the predicted effectiveness of RFH/SVE in removing and destroying contaminants from the vadose, capillary fringe, and saturated zones and achieving a significant reduction in the ability of the residual to mobilize and contaminate the site's groundwater. The major problem at Site S-1, as identified in the RI (HNUS, 1994), is a contaminated groundwater plume originating from the sump area. Chlorobenzene and benzene are the chemicals of concern.

The sump area contains approximately 28,000 tons (23,333 cubic yards) of contaminated soil in an area 300 feet long by 150 feet wide by 25 feet deep. No attempt will be made to heat the entire volume. RFH will be used to enhance the removal of VOCs (mainly chlorobenzene, BTEX, and dichlorobenzenes). Removal and destruction of lighter SVOCs and POLs will also occur. See Section 7 for details.

8.1.4 Design Limitations

The accuracy of the system design and projected system performance is limited to the accuracy of the information and experience of the personnel used in development of the designs. If actual site and operating conditions vary substantially from the data used in the designs, system performance will vary accordingly. As concluded in Sections 5 and 6:

- The availability of field-proven RFH equipment will have a dominant impact on all other aspects of design and operations.
- A major limiting factor in presenting patented RFH subsystem design information and procedures is the proprietary nature of the knowledge.
- RFH/SVE system design is based on a complex set of electrical, chemical, and physical specifications.

A properly designed system must operate under site specific-conditions, incorporate existing components where possible, and maximize automatic operation for economy and efficiency. To improve efficiency, the design will incorporate development modifications based on lessons learned from the demonstrations at Site S-1 and any new developments from other recent and ongoing RFH/SVE projects. As a result, system design should be viewed as a flexible, iterative process and subject to change during installation and operation to accommodate any field variance from the design specification. In addition actual field-observed conditions at Kelly AFB are known to vary widely from one area to another. Modification of the conceptual design to some degree during final design is considered likely.

8.2 GENERAL DESIGN AND OPERATIONAL SPECIFICATIONS

Design and operational specifications are based on the preceding sections and define component selection, site preparation, and operating conditions. These specifications take into consideration the demonstration project's research and development objectives, site characterizations, expected emissions, regulatory requirements, health and safety concerns, sampling strategies, and potential design modifications for increased system efficiency. General design and operational specifications common to both techniques are, as follows:

- The RFH inground components will be placed between the Phase I IITRI and KAI heated areas.
- One trailer will be required to house the site office and RF control hardware and instrumentation and a GC laboratory.
- One trailer will be required to house the sources and store materials, parts, and tools.
- Power will be available from existing power distribution lines.

- Two telephone lines will be required for personal and computer communications.
- The RF sources will have a total power output of 100 kW.
- Operating frequencies will be the same as for the pilot demonstrations.
- SVE will be accomplished by vertical vented wells, with horizontal wells for back-up and safety.
- Vented wells will be connected to a manifold system for SVE control.
- A system of ground pressure measurement wells will be placed around the perimeter of the heated area to monitor SVE operational parameters.
- SVE will utilize a regenerative blower system to provide extractive force.
- Vapor treatment will utilize a catalytic oxidation (CAT/OX) unit.
- Propane will provide fuel for the CAT/OX unit.
- Soil samples will be collected for analysis before and after operations.
- A gas chromatograph (GC) for vapor stream analysis screening will be housed in the control trailer.
- Four high level vapor stream analyses will be performed during operations to validate and calibrate GC results.

The decision to use a regenerative blower for vacuum power and a catalytic oxidation vapor treatment unit is based on two factors. First, a lesson learned early in Phase I, a custom-designed, full-scale vapor treatment system would be capital intensive and complex to operate and monitor. The ejector and flare VT system used for the Phase I demonstrations was project-specific and designed to be safe, reliable, and economical. This system was highly resistant to corrosion, minimized the explosive potential, and had few moving parts. Also, Kelly AFB already owned the flare. Second, the existing ejector/flare VT is limited by air discharge permitting limitations. Conventional components allow standardization of VT for conceptual model simplification. Both components are well known from extensive operational experience and have a wide selection of vendors. Other systems would require site and project specific evaluation and design beyond the scope of this conceptual design.

8.3 IITRI DESIGN AND OPERATIONAL SPECIFICATIONS

The following sections present system specifications in terms of site specific characteristics and IITRI technique requirements.

8.3.1 Basic IITRI RFH System Specification for Site S-1

- The RF applicator system will consist of two excitor rows and three ground rows.
- Excitor electrode rows will be 32 feet long.
- Excitor electrodes will be 20 feet in length.
- Ground electrodes must be 8 feet longer than the excitor electrodes.
- The ground row will extent, at a minimum, two electrodes (8 feet) beyond the excitor rows.
- Treatment will occur from 0 to 19 feet deep with a 1 foot deep fill of drill cuttings placed over the treatment zone for a total of 20 feet.
- 100% of all drill cuttings will be placed in the one foot layer and treated during operations.
- An insulated vapor barrier will be required.
- RF energy will be generated at a frequency of 6.78 megahertz (mHz).
- Manpower will consist of six people; one senior radio operator with two junior assistants, one site engineer, and two senior technicians.

8.3.2 IITRI System Components

8.3.2.1 RFH

The major components of the IITRI system will be the RF source, coaxial transmission line, matching networks, RF chokes, electrode array, insulated vapor barrier, RF shielding and electrical grounding, and instrumentation. Conceptual specifications for components will be as follows:

- Four 25-kW sources will be linked. A rigid, 6-inch diameter, copper coaxial line will transfer RF energy from the sources to the mid point of the excitor electrode row.

- Two remotely adjustable matching networks will be installed in series between the RF power source and the electrode array. The first will reduce the standing wave ratio to about 7:1, and the second will further reduce it to about 1.05:1.
- Three chokes will be installed in the IITRI system. One will be placed between the two matching networks to suppress currents flowing back toward the RF source. A second choke encircling the thermocouple leads will protect the monitoring equipment. A third will be placed on the conduit connecting the vapor collection manifold and the vapor treatment system to prevent current flow to the VT system and protect persons working on the treatment equipment.
- A ground electrode spacing of 4 feet, an excitor electrode spacing of 4 feet, and a row separation of 8 feet will be used for the proposed demonstrations. The excitor electrodes will be 2-inch diameter copper (excitor at row ends are 3-inch diameter) and will be connected to the coaxial line by a copper manifold at the center of the excitor electrode row. The ground electrodes will be 3-inch diameter aluminum connected as specified below.
- The insulated vapor barrier will consist of three layers; a primary barrier, a insulation barrier, and a secondary barrier. The primary vapor barrier will consist of a 60-mil sheet of silicon rubber reinforced with fiberglass, able to withstand temperatures up to 250°C (475°F), and resist puncture. A 2-inch insulation layer will be placed on the primary barrier. A 20 mil single sheet of nylon-reinforced plastic will then be placed over the insulation as a secondary barrier. The barrier will be fabricated to be dragged on and off the treatment area. The layers will be quilted together to form a one piece blanket 64 feet long and 52 feet wide.
- RF shielding and grounding consists of a ground plane and a 8-foot radius corrugated aluminum connected to the ground row electrodes, each constructed of aluminum. The shield will have aluminum plate end walls with entrance doors. A weather cover or tarp placed over the shield will prevent precipitation and surface run-off from contacting the excitor electrodes and causing short circuiting. For additional personnel safety expanded aluminum mesh plates will be placed on the insulative vapor barrier and physically connected to the ground row electrodes. The shield will have an air evacuation blower to prevent moisture build-up within the shield. Air evacuation reduces possible electrical shock hazards and prevents possible build-up of harmful vapors within the shield.

- RFH subsystem instrumentation will consist of a standing wave ratio meter, an ohmmeter, and a watt meter, each linked to an operation computer (see Section 5). Thermocouples and thermowells will be installed at selected locations to monitor temperatures. These locations will provide temperatures in, around, and beneath the heated volume at three depths.

8.3.2.2 SVE

The SVE system for the IITRI demonstrations will consist of a vapor containment barrier, extraction wells, redundant regenerative blowers, and a collection and transfer manifold.

- Vapor containment will be accomplished by the primary barrier used in the construction of the insulated vapor barrier. The barrier must extend at least 12 feet beyond the outside edge of the heated zone. The outer edges will be secured to prevent air infiltration through gaps between the barrier and soil surface. All RF power conduits, extraction piping, and miscellaneous hardware will be located below the ground surface to simplify barrier construction and adjustment. Required perforations and connections will be overlapped and/or sealed with heat-resistant tape or silicone chalk.
- Selected vertical ground electrodes will serve the dual functions of heating and vapor extraction. Approximately every third ground electrode will be vented for vapor extraction by drilling 0.25-inch diameter holes on concentric patterns over the required length of the electrode. Vent hole frequency will be one per 1.5 inches of vented length. Material requirements prevent the use of conventional screened well casing. The diameters of the vertical electrodes are based on both vapor- and current-carrying capacities. Appropriate connections will be made between the tops of the electrodes and the transfer conduits to provide both vapor conduction paths and electrical grounding. For Site S-1 the end electrodes will be vented from 10 to 20 feet below ground and will alternate with electrodes vented between 2 feet and 10 feet below the ground. To prevent the vented electrodes from acting as conduits capable of draining any condensate into deeper cooler soil, the electrodes will be plugged at the depth of the excitor electrodes. The space between the electrodes and boring walls will be filled with a soil mixture similar to the site soils for electrical connection and structural support.

- Horizontal vapor extraction pipes will be placed at ground surface outside the ground electrodes. Horizontals will be constructed from 2-inch diameter fiberglass epoxy pipe covered by a 1.5 foot layer of drill cuttings. The pipe will be vented with 0.25-inch diameter holes drilled at rate of one every 1.5 inches over the length of the ground electrode.
- The two piping systems will be joined in a collection and transfer piping manifold constructed from rigid fiberglass epoxy pipe with adequate valves and ports for control and monitoring. Vapors will be transferred to the Catalytic Oxidation unit for treatment by a system of flexible hoses. These hoses will be wrapped or buried for insulation depending on use.
- Electric regenerative blowers will be used for extractive force to provide a soil vacuum. The blowers will be explosion proof and corrosion resistant. The blowers will be capable of providing 5 to 50 inches of H_2O vacuum at the extraction well head and a flow rate of between 100 and 300 scfm.

8.4 KAI SYSTEM DESIGN AND OPERATIONAL SPECIFICATION

8.4.1 System Specification

- Eight antenna wells will be required.
- Antenna casings will be placed in a 16 feet by 16 feet square array.
- Treatment will occur from 0 to 19 feet deep with a 1 foot deep fill of drill cuttings placed over the treatment zone for a total of 20 feet.
- 100% of all drill cuttings will be placed in the one foot layer and treated during operations.
- An insulated vapor barrier will be required.
- Antenna wells will be cased to a depth of 24 feet.
- RF energy will be generated at a frequency of 27.58 MHz.
- Manpower will consist of four people; one senior radio operator with junior assistant, one site engineer, and one senior technician.

8.4.2 KAI System Components

8.4.2.1 RFH

The major components of the KAI subsystem will be the source, coaxial transmission line, antenna array, insulated vapor barrier, RF shielding and electrical grounding, and instrumentation. Conceptual specifications for components will be as follows:

- Four 25-kW sources will be linked. A rigid 2-inch diameter copper coaxial line will transfer RF energy from the sources to the antennae.
- Eight antennae, each approximately 10-feet long, will be placed inside antenna wells cased with 4.5-inch ID fiberglass epoxy guide sleeves that are heat rated to 200°C, non-conductive, and invisible to RF energy. Each well annulus will be backfilled with sand and sealed at ground level with a 2-foot bentonite clay plug. The antenna wells will be sealed at the top with rubber gaskets and the hole purged with nitrogen during operation to cool the guide sleeves. Antennae will be constructed from solid copper rods surrounded by an outer aluminum hull. Teflon rings and spacers will be required to structurally support the inner rod and prevent contact between the aluminum hull and the guide sleeve. Light weight 20-foot vertical aluminum frame towers will be required to lower and raise the antennae for positioning and to remove the antennae for maintenance. Tower frames will consist of 1-inch OD aluminum tubes with 0.065-inch wall thickness cross braced with 3/8-inch diameter solid rods. The towers will be supported by 1/4-inch steel base plates connected to the guide sleeves at ground level for foundation and guide wires connected at the tops and staked to the ground in three directions (or as required) for vertical support.
- The insulated vapor barrier will consist of three layers; a primary barrier, a insulation barrier, and a secondary barrier. The primary vapor barrier will consist of a 60 mil sheet of silicon rubber reinforced with fiberglass, able to withstand temperatures up to 250°C (475°F), and resist puncture. A 2-inch insulation layer will be placed on the primary barrier. A 20-mil single sheet of nylon-reinforced plastic will then be placed over the insulation as a secondary barrier. The barrier will be fabricated to be dragged on and off the treatment area. The layers will be quilted together to form a one piece blanket 72 feet long and 40 feet wide.

- A 10 by 10 foot rectangular RF ground plate constructed from flat 12 gauge 2.5 X 5 foot expanded mesh aluminum sheets will be placed around each antenna well above the vapor barrier and mechanically connected to the tower base plates. The towers and base plates will be electrically grounded by an array of six 4-foot long, 0.5-inch diameter copper coated grounding rods driven into the ground and connected to the base plate by 2-0 bare copper wire. All connections will be by mechanical clamps.
- The KAI RFH subsystem instrumentation will consist of a standing wave ratio meter, an ohmmeter, and a watt meter, each linked to an operation computer (see Section 5). Thermocouples and thermowells will be installed at selected locations to monitor temperatures. These locations will provide temperatures in, around, and beneath the heated volume at three depths (see Section 6).

8.4.2.2 SVE

The SVE system for the KAI demonstrations will consist of a vapor containment barrier, vertical extraction wells, horizontal extraction wells, a collection and transfer manifold, and regenerative blowers.

- Vapor containment will be accomplished by the primary barrier used in the construction of the insulated vapor barrier. The barrier must extend at least 12 feet beyond the outside edge of the heated zone. The outer edges will be secured to prevent air infiltration through gaps between the barrier and soil surface. All RF power conduits, extraction piping and miscellaneous hardware will be located below the ground surface to simplify barrier construction and adjustment. Required perforations and connections will be overlapped and/or sealed with heat-resistant tape or silicone chalk.
- The extraction wells will be cased with 2-inch ID temperature resistant fiberglass epoxy pipe developed with sand pack and a minimum 12-inch bentonite seal at the top. For Site S-1, every other well will be vented from 10 to 20 feet below ground and will alternate with wells vented between 2 feet and 10 feet below the ground. The space between the casing and boring walls will be filled with sand for support.

- Horizontal vapor extraction wells will be constructed from the same fiberglass epoxy pipe as the extraction wells and covered by a 1.5 foot layer of drill cuttings. Two 10-foot vented sections of pipe will be placed within the antenna array and piped into the manifold. The pipe will be vented with 0.25-inch diameter holes drilled at rate of one every 1.5 inches over the length of the ground electrode. See Section 6 for design details.
- The vertical and horizontal extraction wells will be joined in a collection and transfer piping manifold. The manifold will be constructed from the same fiberglass epoxy pipe as the extraction wells and valved and ported to allow for flow adjustment and vapor stream property measurement.
- Electric regenerative blowers will be used for extractive force to provide a soil vacuum. The blowers will be explosion proof and corrosion resistant. The blowers will be capable of providing 5 to 50 inches of H_2O vacuum at the extraction well head and a flow rate of between 100 and 300 scfm.

8.5 RF/SVE FIELD OPERATIONS

8.5.1 General

System construction and operation are key factors in RFH/SVE efficiency, effectiveness, and cost. All aspects of operation will be dominated by personnel health and safety concerns and the possibility of equipment damage and breakdown. Operational procedure and personnel will be selected and organized to effect safe efficient operations with minimal manpower. During RF system operation two site personnel will be present 24 hours per day, 7 days per week for the IITRI method and 12 hours per day 6 days, per week for the KAI. The site will be maintained in an neat and orderly fashion during operations. Field activities will include:

- site preparation, system construction and set-up,
- system operations, and
- system dismantling and site restoration.

In order to limit access, the site will be completely surrounded by an 8-foot high chainlink security fence. Site access will be limited by the site manager (SM) and/or the site safety officer (SSO). All individuals that entry or leave the site boundaries will sign in and out at the site office. During all site operations, an area encompassing the RFH/SVE system will be regarded as the exclusion zone.

This zone will be controlled by traffic cones, warning tape, and physical barriers, as appropriate. Only authorized personnel will be permitted in the exclusion zone during operations. A contamination reduction zone will be located adjacent to the exclusion zone for the decontamination of personnel and equipment. An emergency eye wash and overhead shower will be located within this zone. A support zone will be located at the clean side of the contamination reduction zone. The support zone will be readily accessed by motorized vehicles.

Personnel and subcontractors that enter the exclusion zone will have completed 40-hour Health and Safety Training (OSHA 29 CFR 1910.120). The site manager and the SSO will have completed the 8-hour Site Supervisors Training (OSHA 29 CFR 1910.120). A site safety briefing to include all subcontractors and site workers will be held just prior to the start of all site activities. In addition, the start of each work week, the SSO shall conduct a short health and safety meeting. All meetings will be documented in the Site Manager's or the Site Safety Officer's Project Logbook. Authorized personnel will include only those with OSHA training certificates, respirator fit test certificates, and medical clearances on file in the site office.

The SSO will exercise the authority to upgrade or downgrade levels of personnel protection as necessary during site preparation and RFH system operation. The level of personnel protection equipment (PPE) will be based in part on the readings of air monitoring equipment and existing weather conditions, particularly wind velocity and direction. Field activities will be performed beginning in Level D. Hard hats, safety glasses, and steel toe work shoes are required at a minimum. When handling any equipment, soil, or debris, chemical resistant gloves will be worn. If required by air monitoring, PPE may be upgraded to level C by the addition of Tyvex overalls and OSHA approved disposable dust respirators (3M-9970 or equal).

The following four real-time monitoring instruments will be used during operation.

1. Photo Ionization Detector (PID) (i.e., HNu)
2. Flame Ionization Detector (FID) (i.e., OVA)
3. Combustible gas/explosimeter (i.e., LEL/O_2)
4. Electric and magnetic field monitor

An initial site surveillance will be conducted using instruments 1, 2, and 3 prior to any site activities. During pre-test sampling and drilling, monitoring will be conducted using instruments 1, 2, and 3. During RF system operation, all listed instruments will be used for monitoring. All instruments will be in good working order and calibrated as required by regulation and manufacturer's recommendations.

8.5.2 Site Preparation and System Construction

Site preparation and system construction will include activities to ready the site for system set-up, placement and set-up of system components, and operation. Tasks will include activities associated with the operation of the RF, SVE, and VT subsystems and consist of fencing, drainage control grading, concrete transformer pad, electrical lines, placement of trailers, installation of the natural gas line, soil boring, sample collection, well development, piping fabrication, etc. Contaminated materials (e.g., soil and debris from trenching, grading, soil boring, soil sampling, and PPE) will be encountered and/or generated during site preparation.

8.5.3 System Operations

The (RFH) demonstration is expected to be conducted under moderate climate conditions, so no heat/cold stress monitoring will occur. However, heat stress monitoring may become necessary if ambient temperature is at 70^{O}F or above. This is due to the normal hazards of hot weather, enhanced by the RF heating of the soils. The site safety officer will monitor all crew members for signs and symptoms of heat stress. Possible emissions and materials encountered and/or generated during operations include gas from vapor extraction, liquid from vapor extraction, emissions from vapor treatment, and radio frequency radiation. Electrical consumption, RF power, gas and liquid flows, pressures, and temperatures must be monitored during operations.

VT activities will be performed in Level D PPE with chemical resistant gloves. In the event of a vapor barrier leak, SVE and VT operations will be discontinued and an upgrade to Level C PPE will be made before repair. During sampling and analysis activities, the possibility of contact with contaminated gases and liquids increases. During operation vapor stream sampling and analysis will be required on a regular basis. VOCs, SVOCs, and TPHs will be analyzed weekly. This data will be used as a screening tool to monitor performance. A trained engineer will collect and analysis all samples. Samples will be collected before the vapor treatment subsystem to evaluate process status. Samples from the vapor treatment unit's discharge stack will be collected to evaluate and document vapor treatment effectiveness.

Operation at an authorized industrial, scientific, and medical (ISM) designated frequency minimizes the FCC requirements. Site workers must be protected from dangerous levels of radiation and system operation must not interfere with communication or security operations. Since radio frequency heating will operate at frequencies of 6.78 MHz for IITRI and 27.13 MHz for KAI, monitoring will be performed for electric and magnetic fields to insure that all site activities are in compliance with American National Standard ANSI C95.1-1982 . In addition, Department of the Air Force AFOSH Standard 161-9 for exposure to RF radiation shall apply. Careful attention to the following items will preclude most problems:

- Major changes in operation must be made or supervised by a skilled, experienced operator. Emergency shutdowns are the only exceptions.
- Operating plans must be approved by Base communications and security personnel.
- The RFH system must be designed to reduce spurious radiation.
- The applicator array must be adequately shielded and grounded to protect site workers and prevent interference with other electronic systems.

A principal physical hazard during the actual RF heating process is the potential for electrocution. As the system utilizes a 480-volt feed and operates at a maximum of 300 amps, all electrical power must be grounded appropriately with the necessary circuit interrupters. All applicable OSHA standards for electrical safety shall apply (29 CFR 19710.500).

8.5.4 System Dismantling And Site Restoration

System dismantling will include teardown, decontamination, pack-up, and shipping of system components. Rented or leased equipment will be dismantled, disconnected, decontaminated, and packed for return or pick-up as appropriate. The site will be restored to pre-existing conditions. Site S-1 will be graded and grassed or graveled.

8.6 COST ESTIMATES

Cost estimates are based on data generated during the Preplanning and Phase I. While dominated by actual experiences during the Phase I design, procurement, and field activities, the estimates also reflect logistical and capital cost knowledge gained during the Preplanning Phase. Estimates are conceptual in nature. Table 8-1 and 8-2 present summaries of estimated costs for the implementation of Phase II at Site S-1. These estimates assume purchase of all hardware by the USAF and do not reflected commercial costs. Table 8-3 and 8-4 present summaries for implementation of Phase II under a commercialized scenario with capital equipment amortization, long term maintenance, and salvage value. See Appendices A.12 and B.7 for details.

TABLE 8 - 1
IITRI COST SUMMARY - PHASE II
RF SOIL DECONTAMINATION DEMONSTRATION

ITEM	UNIT COST ($)	SUBTOTALS
RF SOURCE		**$883,852**
RF TRANSMITTERS	242,000	
RF CONTROL UNIT	600,000	
ELECTRICITY	41,852	
RF APPLICATION		**$25,244**
EXCITOR ELECTRODES	11,280	
COAXIAL TRANSMISSION LINE	2,300	
GROUND ELECTRODES	11,664	
RF SHIELD		**$7,217**
DOGHOUSE	6,664	
MESH SCREEN	553	
MEASUREMENT/CONTROL		**$21,670**
THERMAL MEASUREMENT WELLS (TMW)	66	
VACUUM MEASUREMENT WELLS (VMW)	29	
THERMOCOUPLES (TCs) AND WIRE	3,437	
VACUUM/PRESSURE GAUGES	138	
GAS CHROMATOGRAPH	18,000	
VAPOR COLLECTION/TRANSFER PIPING.		**$3,541**
VAPOR BARRIER	1,492	
GROUND ELECTRODE PIPING	1,188	
HORIZONTAL EXTRACTION PIPING	363	
EXTRACTION MANIFOLD	497	
VAPOR EXTRACTION/TREATMENT		**$251,700**
REGENERATIVE BLOWER	1,700	
CATOX TREATMENT UNIT	250,000	
SITE SUPPORT		**$80,050**
UTILITY TRUCK	35,000	
CELLULAR TELEPHONE	4,875	
MISCELLANEOUS ODCS	47,560	
FENCING	9,200	
GRAVEL	2,500	
CONCRETE	7,108	
WASTE DISPOSAL	7,108	
LIGHTS	1,700	
SUBCONTRACTOR SUPPORT		**$190,954**
DRILLING FOR SYSTEM INSTALL	24,664	
IN GROUND SYSTEM ABANDONMENT	23,390	
RF CONSULTANTS	100,000	
ANALYTICAL	42,900	
LABOR		**$477,389**
SITE PREPARATION/SET-UP	55,688	
TREATMENT	403,139	
SITE RESTORATION/DEMOBILIZATION	18,563	
	SUBTOTAL	**$1,941,617**
ODC MARKUP	10.60%	**$155,208**
ENGINEERING, PROCUREMENT, & PROJECT MANAGEMENT	15%	**$219,634**
CONTENGENCY	15%	**$219,634**
	TOTAL	**$2,536,093**

TABLE 8 - 2
KAI COST SUMMARY - PHASE II
RF SOIL DECONTAMINATION DEMONSTRATION

ITEM	UNIT COST ($)	SUBTOTALS
RF SOURCE		**$884,578**
RF TRANSMITTERS	242,000	
RF CONTROL UNIT	600,000	
ELECTRICITY	42,578	
RF APPLICATION		**$208,000**
ANTENNA	132,000	
ANTENNAE CASING	27,200	
COAXIAL TRANSMISSION LINE	21,600	
ANTENNA TOWERS & BASE PLATES	27,200	
RF SHIELDING & GROUNDING		**$1,104**
MESH SCREEN	256	
GROUNDING	848	
MEASUREMENT/CONTROL		**$20,173**
FIELD MEASUREMENT WELLS (TMW)	377	
PRESSURE MEASUREMENT WELLS (VMW)	254	
THERMOCOUPLES ASSEMBLIES	1,405	
VACUUM/PRESSURE GAUGES	138	
GAS CHROMATOGRAPH	18,000	
VAPOR COLLECTION/TRANSFER PIPING		**$2,102**
VAPOR BARRIER	835	
HORIZONTAL EXTRACTION PIPING	114	
EXTRACTION MANIFOLD	1,153	
VAPOR EXTRACTION/TREATMENT		**$251,700**
REGENERATIVE BLOWER	1,700	
CATOX TREATMENT UNIT	250,000	
SITE SUPPORT		**$68,597**
UTILITY TRUCK	35,000	
CELLULAR TELEPHONE	4,875	
MISCELLANEOUS ODCS	41,815	
FENCING	9,200	
GRAVEL	2,500	
CONCRETE	1,400	
WASTE DISPOSAL	7,108	
LIGHTS	1,700	
SUBCONTRACTOR SUPPORT		**$140,802**
DRILLING FOR SYSTEM INSTALL	8,610	
IN GROUND SYSTEM ABANDONMENT	9,493	
RF CONSULTANTS	80,000	
ANALYTICAL	42,700	
LABOR		**$259,875**
SITE PREPARATION/SET-UP	37,125	
TREATMENT	204,188	
SITE RESTORATION/DEMOBILIZATION	18,563	
	SUBTOTAL	**$1,836,931**
ODC MARKUP	10.60%	**$167,168**
ENGINEERING, PROCUREMENT, & PROJECT MANAGEMENT	15%	**$236,558**
CONTENGENCY	15%	**$236,558**
	TOTAL	**$2,477,216**

TABLE 8-3
IITRI COMMERCIAL COST DETAILS
RF SOIL DECONTAMINATION DEMONSTRATION

ITEM	%	COST
LABOR		$477,389
ODC's		$221,526
CAPITAL		$375,704
SUBTOTAL		$1,074,619
ODC MARKUP	10.60%	$63,306
ENGINEERING	15%	$161,193
CONTINGENCY	15%	$161,193
TOTAL		**$1,460,312**

*INCLUDES 10.6%MARKUP

TABLE 8-4
KAI COMMERICAL COST DETAILS
RF SOIL DECONTAMINATION DEMONSTRATION

ITEM	%	COST
LABOR		$259,875
ODC's		$184,752
CAPITAL		$435,644
SUBTOTAL		$880,271
ODC MARKUP	10.60%	$65,762
ENGINEERING	15%	$132,041
CONTENGENCY	15%	$132,041
TOTAL		$1,210,115

9.0 CONCLUSIONS AND RECOMMENDATIONS

Conclusions and recommendations are based on lessons learned during the Preplanning Phase and the Phase I demonstrations. The primary objectives of the project were meet. The secondary objectives were addressed during the project with varying success.

9.1 CONCLUSIONS

9.1.1 Primary Objective Number One

Primary objective number one, to broaden the proven range of the RF technology applicability in low permeability soil, was met. This objective is evaluated with CERCLA guidelines for process option screening for effectiveness. The guidelines are modified due to the research and development nature of this project. Applicability is based on meeting five criteria; (1) the potential for handling the estimated areas or volumes of media; (2) the potential impacts to human health and the environment during the construction and operation; (3) the potential for the reduction of contaminant toxicity, mobility, and volume; (4) the permanence of the process, and (5) the reliability of the process with respect to the contaminants and conditions at the site.

The Potential for Handling the Estimated Areas or Volumes of Media

Radio frequency energy can be effectively applied to heat low permeability soils in situ. Available RF generator capacity creates a trade-off between system size and the time required for operation. Any size area or volume could be heated with adequate RF generating capacity (see Section 5 for detailed discussion).

The Potential Impacts to Human Health and the Environment During the Construction and Operation

Impacts to human health and the environment are possible during construction and operation of an RFH system. Except for RF radiation, these impacts are fairly standard for remedial projects with some special concerns for heat. RF shielding and site monitoring are required to eliminate radiation hazards (see Section 5 for detailed discussion).

The Potential for the Reduction of Contaminant Mobility, Toxicity, and Volume

Contaminants were removed and destroyed during the demonstrations at Site S-1, so a direct reduction in contaminant volume occurred with a corresponding reduction in contaminant mobility and potential toxicity. Although possible, RFH has not been used to destroy contaminants in place. During system operations vapor monitoring identified contaminant removal. Contaminant mobility enhancement and removal was also suggested in the comparison of pre- and post soil analyses.

The Permanence of the Process

The contaminants removed during operation were removed permanently and the resulting vapors were burned in a flare. Residual vapors were discharged to the atmosphere after flaring.

The Reliability of the Process with Respect to the Contaminants and Conditions at the Site

In light of information from the Site S-1 RI (HNUS, 1994) and the completed tests, operational concepts should be modified to address the remediation of the contaminated groundwater sourcing from the sump area. No problems from corrosion, acidity, flammability, explosibility, or ignitability were encountered. Site conditions presented no difficulty beyond the normal expected for a research and development effort.

9.1.2 Primary Objective Number Two

Primary objective number two, to more accurately assess the implementation requirements of commercial-scale systems, was met. Implemetability is based on meeting four criteria; (1) technical feasibility; (2) availability of vendors, equipment and waste disposal facilities and services; (3) administrative feasibility, and (4) special long-term maintenance and operational requirements.

Technical Feasibility

The demonstration of the IITRI and KAI RFH techniques at Site S-1 further documented the ability of the developers to design and implement in situ RFH of soil. As with all developing technologies technical feasibility is a problem. Even the patent holders have limited experience and knowledge due to site specifics of soil type, moisture, contaminants, geology, etc. Both developers made major improvements during the Phase I demonstrations. Some examples follow:

1. IITRI

- Aluminum ground electrodes were used to replace copper for material cost reduction and increased durability .

- A simplified RF shield structure was demonstrated, reducing materials and construction costs. Previous shields were completely custom fabricated. The new design incorporates off-the-shelf aluminum culvert sections.

- The excitor electrodes were deliberately pushed to failure. Several important concepts were documented. First, after the removal of moisture from around the electrodes arcing becomes exaggerated, causing high temperatures and failure, a situation to be avoided in the future. Second, the proximity of groundwater close to the bottom tips of the excitor electrodes also causes exaggerated arcing. System design and operation must take these conditions into consideration.

- Passive surface SVE is not efficient in deep, low permeability soils. SVE must be designed and operated to minimize extracted air volumes for vapor treatment cost reduction.

2. KAI

- During operation, the standard (by code) electrical hook-up was not adequate for full automated RF source operation. To assure uninterrupted power delivery, an uninterruptable power source is required when connected to a local power grid (as at Site S-1).

- The use of relatively inexpensive rigid coaxial transmission lines require major system shutdown for antenna movement. Flexible coaxial transmission lines should be used for system flexibility and efficiency.

- Antenna guide casing or sleeves require temperature-resistant materials which are invisible to RF energy. Although a relatively cheap fiberglass epoxy pipe normally made for use in petroleum refineries exists, the depressed state of the petroleum industry has caused a void in the availability of this product. Manufacturers are unwilling to run large batches (12,000 linear feet) for a small order (three 24 foot sections). Therefore, the antenna sleeves had to be custom made for Phase I.

- Materials limitations for antenna sleeves and vapor extraction were evaluated during the demonstration. Antenna Sleeve No. 1 was heated to 232.4°C before deforming during an antenna malfunction. Antenna Sleeve No. 2 withstood temperatures of 150°C (the design temperature) for extended periods with no apparent effect on operations. The standard fiberglass epoxy pipes used for vapor extraction withstood temperatures in excess of 90°C (vapor temperature) for extended periods with no apparent effect on operations. A visual inspection after pipe removal revealed no deformation.

Availability of Vendors, Equipment, and Waste Disposal Facilities and Services

Only two vendors (e.g., IITRI and KAI) are actively engaged in RFH/SVE and the majority of design methods for RFH systems are proprietary to IITRI and KAI. IITRI is an R&D organization not in position to commercialize the triplate method. Non-exclusive licenses now in place with two large US companies should help. An investment in developing the method is required for increased automation and simplification.

Waste disposal facilities and services are location- and contaminant-specific. These services were adequately available during the Phase I demonstrations.

Administrative Feasibility

The USAF has specific regulations for the use of electromagnetic (RF) energy on or around USAF bases. Regulations require that permits be issued by the command headquarters at Wright-Patterson AFB. TNRCC regulators have followed the Phase I progress and have voiced no concerns about the technology. The FCC has also been well informed of the demonstration activities and view the use of RF energy in this way as covered by the ISM Band regulations. Although no FCC permits were required for the Phase I demonstrations, the FCC should be notified before the start of field activities. Community acceptance could be a problem due to the mystique of electromagnetic energy.

A standardized system with pre-approved frequencies would ease implementation and allow rapid mobilization for implementation. The need for frequency approval at USAF sites slows design and mobilization. Past tests and demonstrations have required studies to define dielectric soil properties for choosing optimal heating frequencies. For optimal operation, frequency should be variable with soil moisture. Since electrical consumption is only 17% of the cost of the process, optimization is a relatively minor factor in overall process efficiency. This fact enables system standardization (equipment, materials, operating frequencies).

Special Long-Term Maintenance and Operational Requirements

Due to the developing nature of RFH/SVE, little is now known concerning long-term O&M requirements. Although RF transmission is a well established technology, in situ RFH of soil is relatively new. Long-term data will be slow to accrue for the following reasons:

- The process requires substantial capital investment. Due to unknown market potential, private industry will be cautious and slow to commit development resources.

- Due to conservative planning, design, and operation inherent in R&D activities, demonstrations and tests take considerable time.

- Site conditions and contaminants are so numerous that many demonstrations will be needed to refine system planning, design, and operation.

9.1.3 Secondary Objectives

Secondary objectives for the demonstration included validation of scale-up parameters, the use of electrodes as vapor recovery vents, evaluation of vertical and horizontal transport of contaminants through soil, and the removal of semi-volatile organic compounds (such as phthalates) from soil.

Validation of Scale-Up Parameters

As presented in the preceding sections and within the appendices, substantial cost and operational data was gathered during the Preplanning Phase and Phase I. Section 8 presents a conceptual design and operation model based on the data generated during these Phases with detailed cost estimations for Phase II operations. The costs presented reflect actual experience and incorporate few potential cost reductions concepts developed during field activities. These concepts should be further studied and tested and may provide substantial cost reductions for Phase II.

The Use of Excitor Electrodes or Antenna Wells as Vapor Recovery Vents

Recent demonstrations by IITRI and KAI, prior to the Phase I demonstrations, revealed problems with the use of excitor electrodes or antenna wells as vapor recovery vents. Therefore, due to budget limitations, no attempt was made to extract vapors from excitor electrodes or antenna wells .

Evaluation of Vertical and Horizontal Transport of Contaminants through Soil

Contaminant mobilization factors for SVE design were evaluated during the demonstrations by the IITRI tracer test and the measurement of ground pressure during the KAI demonstration. The actual measurement of a permeability increase (with moisture removal) was accomplished for the first time. SVE operational data collected is also valuable for controlling the zone of SVE influence during RFH/SVE operation. Contaminants and moisture can be effectively transported through low permeability soils at depths to 18 feet.

The Removal of Semi-Volatile Organic Compounds (such as Phthalates) from Soil

RFH appears to mobilize heavy SVOCs, but unknown phenomenan are at work. Pyrene and bis(2-ethylhexyl)phthalate appear to have been mobilized and/or removed during operation above 20 feet. Pyrene is a solid at ambient soil temperatures and unaffected by SVE.

9.1.4 General Conclusions

Although IITRI and KAI each experienced equipment, material, and operational problems, each system was basically installed and operated as planned. With minor exceptions, schedules were met and costs remained within budget.

The S-1 demonstration was effectively a hot spot treatment. The sump is a source area for a groundwater plume contaminated by benzene and chlorobenzene. Vapor analysis for the two demonstrations documented the removal of both contaminants. During the KAI demonstration, approximately 17 and 1.5 pounds of chlorobenzene and benzene were extracted, respectively. Theses removals are estimated to be 26.5 percent and 37.5 percent of the total chlorobenzene and benzene at Site S-1 (these percentages do not include removals during the IITRI demonstration). Since the concentrations of these chemicals were actually rising when the system was shut down, additional SVE operation would have removed more.

Limited data from a small number of field (pilot) tests now exist. Criteria for selecting technologies for remedial and corrective actions must be well defined, and that is not the case for RFH/SVE. Often innovative technologies are used only after all other options are rejected.

RFH/SVE is a technology with the potential, through cost reduction, to be a preferred technology. Costs can be decreased to levels competitive with other high technology options (surfactants, steam injection, other in situ heating methods) for enhancing contaminant removal. Costs will decrease significantly as RF heating is further developed. Future commercial applications should require less labor. Technology improvements and increased field experience will result in more efficient operations. The process will become more automated, permitting operation from a remote location.

9.2 RECOMMENDATIONS

1. Further demonstrations (pilot tests) for operational and removal data collection should be performed to define the range of RFH/SVE operating criteria.

2. Future projects should not proceed without competitive bidding. Sites should be selected to allow use of either method. IITRI cannot bid competitively, but the companies licensed to use the triplate method can with IITRI assistance.

3. Sites should be located where conventional SVE has not worked well or has left residuals of heavier contaminants. This situation could provide a valuable comparison of RFH/SVE and conventional SVE.

4. Site S-1 should be monitored in the future to assess the effect on benzene and chlorobenzene concentrations in the groundwater plume, due to the removal accomplished during the demonstrations.

5. Other promising avenues for RFH use should be investigated, for example; existing system enhancement (SVE, bio, pump & treat), deep DNAPL and solids removal and/or mobility enhancement, reduction in toxicity by heat destruction (bond breaking), and fuel spill recovery for recycling.

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APPENDIX A

DRILLING, SOIL SAMPLING, AND INGROUND COMPONENT INSTALLATION

I. INTRODUCTION

Drilling included pre- and post-demonstration phases. The pre-demonstration drilling included soil sampling at designated depths and the installation of the in-ground RFH/SVE components. Post-demonstration drilling also included collecting soil samples at designated locations and abandonment of wells and borings installed during the pre-demonstration phase. Sampling was performed by a registered geologist according to protocal specified in the Sampling and Analysis Plan. (Halliburton NUS, 1993 and 1994) A Mobile B-61 drill rig was used during drilling, sampling, and well installation and abandonment. The IITRI demonstration was conducted in 1993 and the KAI demonstration in 1994.

II. IITRI DEMONSTRATION

Pre-Demonstration Drilling and Sampling

Drilling activities for the IITRI demonstration began with the installation of 3 dewatering wells on January 22, 1993. A dewatering system was required in order to keep groundwater levels below the tips of the excitor electrodes (see Appendix A.8. for Dewatering System details). The dewatering system consisted of a total of 4 dewatering wells, 1 existing well (PW04) and the 3 installed wells (DW01, DW02, and DW03). The dewatering wells were constructed of 6-inch diameter PVC screen and casing and installed in a 14-inch diameter boring. A clean sand backfill was installed around the screen and a bentonite seal placed on top of the sandpack.

Soil sampling and electrode and thermowell installation began on January 26, 1993, and was completed on February 6, 1993 (see Appendix A.1. for details). A total of 3 dewatering wells, 16 ground electrodes, 4 exciter electrodes, and 7 thermowells were installed for a total of 916.5 feet drilled. Hollow-stem augers were used for soil sample collection and to install electrodes and wells. Table C-1 provides auger sizes used for the different types of borings. Soil samples were collected at designated depths using 3-inch diameter split spoons with stainless steel liners. The liners were removed from the split spoon, sealed with a Teflon film and a plastic cap, labeled and recorded on a chain of custody form, transferred to EPA representatives along with the chain of custody form, prepared for shipment, and shipped to the Radian (Austin) laboratory for analysis. A total of 54 soil samples during the pre-demonstration sampling.

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TABLE C-1
DRILLING DATA
IITRI DEMONSTRATION

BORING TYPE	NUMBER OF BORINGS	AUGER SIZE I.D. (inch)	BOREHOLE DIAMETER (inch)	FEET DRILLED	SOIL VOLUME (ft^3)	NUMBER OF DRUMS
PRE-DEMONSTRATION						
DEWATERING WELL	3	10	14	117.5	125.6	
GROUND ELECTRODE	16	4.25	8	446	155.7	
EXCITER ELECTRODE	4	4.25	8	112	41.2	
THERMOWELL	7	4.25	8	241	84.1	
TRACER TEST WELL	1	4.25	8	15	5.6	
SUBTOTALS				814	286.6	16
POST DEMONSTRATION						
SOIL BORING	21	4.25	8	366.5	127.9	
ABANDONMENT	27	3.4	8	719	251	
SUBTOTALS				1085.5	378.9	16

All sampling equipment was decontaminated between samples. The hollow-stem augers used during drilling were taken to the decontamination area established at the Kelly AFB EPCF for decontamination between borings. Stainless steel liners and plastic caps used to collect the soil samples were thoroughly cleaned and wrapped in aluminum foil prior to being used.

The electrodes were placed as specified by IITRI based on site conditions. Some of the electrode borings were drilled deeper than the depth required to set the electrodes. This was necessary to collect soil samples from the designated depths. Boreholes where this occurred were backfilled with bentonite to the depth required to set the electrodes, after the soil samples were collected. Electrodes were set in open boreholes and a special hand-mixed backfill was placed around the electrodes to the surface. Some boreholes required setting the electrodes through the hollow-stem augers to ensure the integrity of the borehole. The sand/clay backfill was prepared on site by mixing sand and clay in the appropriate proportions. A sand backfill was added to the thermowells where the special sand/clay backfill was not required.

At boring EC05 an obstruction was encountered at a depth of 3.8 feet that the augers could not penetrate. A backhoe was used to excavate the obstruction which consisted of 12 pieces of concrete in the fill material. Some of the concrete pieces measured up to 2 feet wide and 2 feet long. The pit that the concrete was excavated from measured 8 feet long, 2.3 feet wide, and 6.5 feet deep. The pit was backfilled with excavated soil and the drilling resumed.

The 286.6 cubic feet of soil cuttings generated during drilling were placed on a plastic liner adjacent to the work area. Approximately 198 cubic feet of soil cuttings were placed and compacted in a one foot thick layer over the heated zone. The remaining 89.6 cubic feet of soil cuttings were placed in 15 drums, labeled, and transported to the Kelly AFB Drum Storage Lot for ultimate disposal.

Post-Demonstration Drilling and Sampling

Post-demonstration drilling and soil sampling began on August 16, 1993 and was completed on August 23, 1993. Soil samples were collected from boreholes drilled adjacent to borings sampled in the pre-demonstration sampling event. The new borings were drilled as close as possible to the existing borings and soil samples were collected from the same depth interval when possible that the sample was collected at in January. In some instances poor sample recovery or obstructions at the original sample depth precluded sampling at the exact same interval. Where this occurred the sample was collected just below the original sample depth where possible. Twenty-one (21) soil borings were drilled for a total of 366.5 feet during the post-demonstration drilling in order to collect soil samples. Hollow-stem augers were used to collect the soil samples.

Additional fieldwork in the post-demonstration drilling phase included abandonment of the soil borings used to collect soil samples as well as abandoning the electrodes and thermowells installed for the demonstration. The electrodes and thermowells were pulled out of the ground using the drill rig and the boreholes were reamed using hollow-stem augers. Of 16 ground electrodes 14 were reuseable. The excitor electrodes were melted inplace and could not be reused. The boreholes were then backfilled with bentonite as approved by the TNRCC. The soil borings were also backfilled with bentonite.

The TNRCC agreed that according to the CAMU concept all soils cuttings could remain on site after the demonstration. Soil cuttings from the post-demonstration drilling were placed on plastic liners when there were no organic vapors detected using an FID. These cuttings were used for site grading backfill during demobilization. For site safety reasons when organic vapors were detected the soil cuttings were drummed. Sixteen (16) drums of soil cuttings were generated and were transported to the Kelly AFB Drum Storage Lot for ultimate disposal.

III. KAI DEMONSTRATION

Pre-demonstration Drilling and Sampling

Fieldwork for the KAI demonstration began on January 10, 1994 with site preparation and pre-demonstration drilling and soil sampling. Three existing wells at the site (S1TW10, S1TW11, and S1PW04) were pulled and abandoned in accordance with TNRCC regulations. The wells were within the demonstration area and required removal.

Pre-demonstration drilling and soil sampling began on January 11, 1994 and was completed on January 19, 1994. A total of 2 antenna, 8 SVE wells, 5 field measurement wells, 6 transducer wells, and 3 thermocouple wells were drilled and installed for a total of 583 feet drilled. Hollow-stem augers of various diameters depending on the type of boring were used (see Table C-2). Soil samples were collected at depths specified in the Sampling and Analysis Plan (Halliburton NUS, 1993). The soil samples were collected using the same methodology used in the IITRI demonstration. A total of 70 soil samples were collected during the pre-demonstration sampling.

The KAI system was installed in the boreholes according to the specifications provided in Appendix B.3. Bentonite and sand backfill were added to the different types of wells as specified. Wells were set inside the hollow-stem augers where the integrity of the borehole was suspect and directly in the boreholes where the boreholes remained open.

Soil cuttings were drummed, labeled, and transported to the Kelly AFB Drum Storage Lot for ultimate disposal. No soil cuttings remained on site except those treated in place. Approximately 203.4 cubic feet of soil cuttings were generated in the pre-demonstration drilling (see Table C-2). Forty (40) drums were used to containerize and transport these cuttings.

Post-demonstration Drilling and Sampling

Post-demonstration drilling and soil sampling began on July 6, 1994 and was completed on July 14, 1994. Post-demonstration drilling and soil sampling activities began on and involved soil sampling and abandonment of the KAI system that was installed in January. Soil samples were collected from boreholes drilled adjacent to borings sampled in the pre-demonstration sampling event. Eighteen (18) new soil borings were drilled adjacent to the boreholes that were sampled in January during the pre-demonstration sampling. A total of 73 soil samples were collected during the post-demonstration sampling. Soil samples were collected from the same depth intervals as the earlier pre-demonstration samples or as close as possible. A total of 434.4 feet was drilled during the sampling phase.

The soil borings were abandoned using the same methodology employed during the IITRI demonstration. The KAI antennae sleeves and various wells were pulled and abandoned. The boreholes were reamed and backfilled with bentonite. The extraction wells and most of the pressure measurement wells had to be overreamed with the piping still in the borehole before the piping could be pulled free of the borehole.

The TNRCC agreed that according to the CAMU concept all soils cuttings could remain on site after the demonstration. Soil cuttings from the post-demonstration drilling were placed on plastic liners when there were no organic vapors detected using an FID. These cuttings were used for site grading backfill during demobilization. For site safety reasons when organic vapors were detected the soil cuttings were drummed. Thirty-five (35) drums of soil cuttings were labeled andtransported to the Kelly AFB Drum Storage Lot for ultimate disposal. Post-demonstration field activities were completed on July 19, 1994.

TABLE C-2
DRILLING DATA
KAI DEMONSTRATION

BORING TYPE	NUMBER OF BORINGS	AUGER SIZE I.D. (inch)	BOREHOLE DIAMETER (inch)	FEET DRILLED	SOIL VOLUME (ft^3)	NUMBER OF DRUMS
PRE-DEMONSTRATION						
ANTENNA SLEEVE	2	6.6	10	55.2	19.3	
VAPOR EXTRACTION WELL	8	4.25	8	193.6	67.6	
FIELD MEASUREMENT WELL	5	4.25	8	126.7	44.2	
TRANSDUCER WELL*	6	4.25	8	143.3	50.0	
THERMOCOUPLE WELL	3	4.25	8	64	22.3	
SUBTOTALS				**682.8**	**203.4**	**40**
POST DEMONSTRATION						
SOIL BORING	18	4.25	8	434.4	151.6	
ABANDONMENT BORING	24	4.25	8	503.5	175.6	
SUBTOTALS				**937.9**	**327.2**	**35**

* Pressure Measurement Well

APPENDIX B

SOIL VAPOR EXTRACTION AND VAPOR TREATMENT SYSTEM DESIGN

I. DESIGN BASIS

The in situ RFH of soil for the enhancement of SVE requires a method of applying a vacuum to extract soil vapor and transfer that vapor to a flare or other treatment system for destruction. The system design incorporated an ejector assembly with transfer piping and operation procedures for integration of the SVE and vapor treatment components.

Design Criteria

Design criteria were estimated from existing site characterization data, assumptions based on past RFH test results, and requirements of air discharge regulations.

Estimated

Maximum vapor flow rate 7,200 scfh
Average vapor flow rate 3,500 scfh
Maximum hydrocarbon concentration 17,000 ppm
Average hydrocarbon concentration 9,500 ppm

Assumed

Maximum vapor temperature 350°F
Normal vapor temperature range 60-300°F
Ejector pressure -30 inches H_2O vacuum

Required

Maximum flare velocity 60 fps (43 expected)
Hydrocarbon emissions 1 lb/hr (0.07 expected)
Maximum chlorinated hydrocarbon emission rate 24 ppm (6.7 expected)

Design Considerations

The design incorporated an existing flare owned by Kelly AFB. An ejector assembly was designed with few moving parts to be inherently simple, rugged, reliable, and mobile. Uninterrupted operation was required, so all equipment was designed to operate over a 180-day period without major maintenance or repair. Basic flow, temperature, and pressure instrumentation were provided along with vapor sampling ports for process monitoring. There were no provisions to cool the vapor stream or condense water and hydrocarbon vapor removed from the treatment volume. The entire vapor stream was flared. Some condensation occurred within the ejector assembly and flare, particularly during the lower temperature stages of the demonstration. Condensate was captured and transported to the Kelly AFB EPCF for treatment. Site personnel coordinated the deliveries with EPCF personnel to assure the availability of treatment capacity.

Safety Considerations

The concentrations of hydrocarbon vapors generated by the RF source in the infiltrating air might have reached the explosive range. The likelihood was very small, but worthy of consideration. The vapor collection manifold and the inlet section of the ejector assembly posed the greatest risks. The anticipated average hydrocarbon content was less than one percent, well below the lower explosive limit (LEL) of the identified hydrocarbons.

Compressed air (75 psig) served for both motive force and vapor stream dilution. This dilution effect kept the composition of the total stream well below the LEL of any hydrocarbons removed from the ground. The additional air reduced hydrocarbon concentrations approximately 50 percent downstream of the ejectors. The all-steel construction of the ejector assembly can withstand overpressures in excess of 200 psig, and should not have been damaged by ignition of the vapors in the system.

II. PROCESS DESCRIPTION

Extracted vapors flowed from the SVE manifold to an ejector assembly. The ejector assembly consists of a collection header piping, a pair of particulate strainers, and a pair of venturi-type air ejectors. A pipeline transferred the vapors from the ejectors to a flare for destruction.

Collection Header

The collection header piping directed the vapors from the SVE manifold through the strainers and ejectors to the transfer pipeline. The collection header is a mobile, skid-mounted unit that includes and supports the strainers and ejectors.

Strainers

Two strainers are provided to remove any particulates larger than 80 microns. Smaller particles will not harm downstream equipment. The line strainers require periodic cleaning. All flow may be routed to one strainer so one may be cleaned while the other remains in service. A drip leg provided in the piping upstream of the strainers allowed condensate in the collection header to be drained and collected for disposal.

Ejectors

A pair of ejectors, powered by a diesel air compressor, supplied the vacuum to remove vapors from the treated zone. Each was located just downstream of the strainers. Each was sized for one half of the maximum design flow. Only one ejector was operated initially to conserve propane fuel and compressed air. The second ejector was available to increase vapor flow rate and/or vacuum as conditions required. A local rental company was able to assure compressor replacement in an hour or two in case of failure. Each ejector could produce a vacuum of 30 inches H_20.

Transfer Piping

The vapor stream from the ejectors flowed to a seal pot at the flare. The piping was elevated and sloped slightly toward the seal pot so condensed vapors flowed to the seal pot and did not collect in low spots in the transfer line. The line was insulated for 20-foot runs on both ends, and the balance of the line was uninsulated.

Seal Pot

The seal pot was mounted on the trailer with the flare system. The seal pot used water as a seal liquid to prevent back flash to the piping from the flare. During the early stages of the test, some water vapor and hydrocarbons in the extracted vapor condensed and collected in the seal pot. Excess liquid flowed into a collection drum for disposal. Seal water evaporated as vapor temperatures rose during the test. Make-up water was added as necessary to maintain the liquid seal level.

Flare

The flare is an existing package unit supplied by Kelly AFB. Vapors from the seal pot flowed through a flame arrestor to the flare stack. Propane gas was added to the mixed vapor stream before combustion at the flare tip. The flare is equipped with an ignitor and an air blower that provides extra combustion air for smokeless operation.

Instrumentation and Control

The ejector assembly is not designed to operate unattended for extended periods. All instrumentation is local and all controls are manual. Vapor stream pressure and temperature indicators are located at the inlet to the ejectors and at the inlet to the flare seal pot. There is also a pressure indicator on the compressed air line at the inlet to the ejectors. Local flow indicators are provided for compressed air flow to the ejectors and total flow at the flare (extracted vapor plus ejector motive air). Vapor flow was calculated as the difference between the two flows. Compressed air and propane flow are controlled by manual valves located upstream of the flow indicators. A vapor sampling port is located at the inlet to the ejectors. Conditions were expected to change gradually over the test period, requiring regular monitoring and adjustments by the operator on site.

III. SYSTEM DESCRIPTION

Equipment Description

The major elements of the SVE and vapor treatment systems are as follows:

- SVE wells and manifold
- a skid-mounted ejector assembly,
- approximately 150 feet of 3-inch carbon steel transfer pipe (supported every 20 feet, minimum),
- a packaged flare system

See Figure C-1, Process Flow Diagram (PFD) for details (Figure 1).

Utilities Requirements

The system is designed to operate with the following minimum utility support:

- A 185 scfm, 100 psig, diesel-driven air compressor is required to provide motive force to the ejectors.
- 220-volt AC electric power is required to operate the sampling pump and the ignition system at the flare.
- Propane gas is required at the flare for supplemental fuel. Two 1000-gallon liquid propane storage tanks were used during the tests.
- Diesel fuel was required to power the air compressor for the ejector assembly. A 600-gallon storage tank was provided on site during the tests.
- Potable make-up water for the flare seal pot was obtained from a faucet located near the northeast corner of the site.

IV. OPERATING PROCEDURE

Pre-Operation Checks

Flare

Flare Systems, manufacturer of the flare, modified the flare piping system and performed a system check-up.

Fuel Levels

Diesel and propane fuel levels were checked before testing. Only small quantities of fuel are required for air compressor and flare tests.

Air Compressor

The oil level in the compressor and the air hose connections at the compressor and ejector assembly must be checked before starting the compressor.

Pre-Operation Testing

Air Compressor

Start the air compressor and monitor the air pressure. The compressor was designed to deliver 100 psig and 185 scfm. Check the air line for leaks.

Flare

1. Press the "push power on" button on ignition control panel. The fuel solenoid will energize immediately. Ignition will occur in 20 seconds (or as set on control panel).
2. Open the air blower control damper.
3. Push the "push blower on" button.

Note: Additional air supplied by the blower is required only during flare testing. During normal RF system operation, air flow from the ejectors is sufficient for combustion. The damper should be closed and the blower should be turned off.

Shutdown Alarm

1. Disconnect the waterproof plug to ignition control box on flare.
2. The system should go into alarm mode in approximately three minutes.
3. The ignition, blower, and solenoid should shut down in this mode.
4. Reconnect the plug to the ignition control box. The system should restart within 20 seconds.

Ejector Assembly

Note: Test each ejector independently. The valves on the skid are tagged.

1. Open both the upstream and downstream valves to the selected strainer.

2. Open the valve to the selected ejector.

3. Open the compressed air valve to direct air from the compressor through the selected strainer and ejector. Observe the air pressure and adjust to 75 psig. One strainer will be on stream.

4. The vapor and air mixture will flow through the ejector and 3-inch transfer line to the flare system.

System Start-Up

Air Compressor

Start the air compressor. The compressor is oversized to operate in intermittent mode. Adjust the compressor to provide 75 psig.

Ejector Assembly

1. Open the valves upstream and downstream of the strainer(s) to supply air to one or both ejectors, as desired.

2. Adjust the compressed air supply valve to supply approximately 140 scfm (or desired flow) to the ejector(s).

3. Ejector operation can be confirmed by observing the Magnehelic gauges provided to monitor pressure drop across the strainer(s).

4. Vapor extraction can be confirmed by observing the combined air/vapor flow meter at the flare; the combined flow should be substantially greater than the compressed air flow to the ejectors.

Flare

1. Ensure the air blower control damper is shut.

2. Press the "push power on" button on ignition control panel.

3. Turn the propane valve on until flame is visible.

4. If smoke is observed, adjust propane flow until smoking is eliminated.

Miscellaneous Operating Criteria

Diesel and Propane Supply

In order to prevent a fuel shortage, the diesel fuel and propane storage tanks were monitored twice daily and the suppliers were given timely delivery notification of fuel needs. Propane consumption varies with the volume and calorific value of the total vapor mixture. Diesel fuel consumption varies with operating conditions. Usage rates must be closely tracked and storage capacity increased, if required.

Strainer Cleaning

The strainer(s) must be cleaned when the vacuum difference across the strainer exceeds 15 inches H_2O (The pressure difference between the pressure gauge upstream and downstream will indicate the total pressure drop). Use the ejector assembly valves to isolate the clogged strainer. Unplug the strainer cap using a wrench, gloves and respirator (Level C). Remove the screen to a plastic pot. Wash it with potable water at the condensate drum by the flare system. Place the wash water in the condensate drum after cleaning a strainer.

Air Flow Control

The air flow must be monitored to maintain the desired pressures through the system. A globe valve is furnished to throttle the system to maintain the desired air flow rate. A local flow meter is furnished. If the valve is wide open and the vacuum level is not being maintained to at least the minimum requirements of approximately 18 inches H_2O, the second ejector should be brought on stream to maintain the vacuum. The vapor flow rate is determined by the difference between the mixed air and vapor flow meter (F1-004) and the compressed air flow meter (F1-013). To maintain the vacuum level at a minimum of 22 inches H_2O, the compressed air volume should be approximately equal to the vapor volume. Due to specific project requirements for continuous operation, arrangements for a standby compressor were made.

Vapor Sampling

The system is furnished with a peristaltic sampling pump to draw the sample vapor to the gas bag furnished by the laboratory. The pump requires 115-volt power. A modular drive system is furnished as a part of the sampling system to control the motor speed and, accordingly, the pump flow rate to fill the gas bag. The samples were analyzed by a certified laboratory.

Safety

Site-specific Health and Safety Plans addressed safety procedures for each test. In addition to site-specific requirements, the following basic procedures are recommended for any operation of the SVE/VT system.

- An exclusion zone must be maintained around the soils being treated, the SVE and vapor treatment systems, and fuel supply tanks.
- Site personnel must be trained in accordance with 29 CFR 1910 and site-specific requirements.
- Smoking on the site is prohibited. The use of open flame inside the secure area is prohibited during flare operation.
- The surface of the piping system may reach a temperature of 300°F or higher. Gloves are recommended during RFH heating operation.
- Safety shoes and hard hats are required all the times around the equipment.
- Goggles or safety glasses are required.

Condensate

The compressed air flows through the ejector to create up to a 30 inches H_2O vacuum at the ejector to draw the vapor from the main manifold. Downstream of the ejector(s), the air and vapor mixture has a pressure of approximately 2 psig and a temperature range of 200°F to 250°F at the peak of soil heating. Condensate may form as heat is lost in the transfer piping. The condensate drains to the seal pot at the flare system, and overflow from the seal pot is collected in a 55-gallon drum. A drum pump is furnished to transfer the condensate from the drum to a wastewater storage tank. During tests at Site S-1, the storage tank contents were periodically transferred to the Kelly AFB EPCF for disposal. Condensate upstream of the ejectors was collected in 5-gallon bottles and transferred to the wastewater storage tank as required.

Electric Tracing

The piping system on the skid is electric traced and insulated to maintain the skin temperature of the piping to compensate for the heat losses and minimize condensation. The electric tracing control is mounted at the piping surface to monitor the skin temperature. The control maintains the selected temperature automatically. The electric tracing is designed for temperatures up to 250°F.

Flare

A modification of the flare piping at the seal pot was required to allow gravity flow of condensate from the transfer line. The seal pot has a sight glass to monitor the level of the water. The level was controlled manually.

APPENDIX C

THE UNIVERSITY OF TEXAS AT SAN ANTONIO
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COLLEGE OF SCIENCES AND ENGINEERING
Division of Life Sciences

25 August 1994

Mr. Clifton Blanchard
Brown & Root
800 Oak Ridge Turnpike, Suite A600
Oakridge, TN 37830

Dear Mr. Blanchard:

We have completed the bacterial analyses of soil samples collected on July 12, 1994, at Kelly AFB (NUS Project No. 3688). The results are tabulated on the accompanying page, along with the results from the first sampling at that site.

Compared to samples taken in February, 1993, microbial levels were reduced for all classes of bacteria enumerated in the July samples. However, the soils are not "sterile". The lack of recovery of oil-degrading bacteria from two of the samples is surprising in light of the fact that both total heterotrophic bacteria and phenanthrene-toluene degrading bacteria were recovered. Suspecting a problem with the oil agar used in the original assay, we repeated this analysis with plates from a different medium lot; however, results again showed very low numbers of bacteria growing on oil agar plates.

If can provide any additional information, you may reach me at [210] 691-4473.

Respectfully,

Barbara E. Moore

Barbara E. Moore, Ph.D.

enc.

NUS Project 3688
Kelly Air Force Base
San Antonio, Texas

Date	Sample No.	Colony-forming units/gm of soil: Total Heterotrophs	Degraders on: Oil	Degraders on: P-T*
19 Feb 1993	KS1-BM01-U0406	6.3×10^5	5.5×10^5	6.0×10^5
	KS1-BM01-U1416	9.0×10^5	1.3×10^6	1.2×10^6
	KS1-BM01-U1719	1.7×10^7	2.1×10^7	2.0×10^7
12 Jul 1994	KRF-BS1-U0608	1.0×10^3	$<1.0 \times 10^2$	1.3×10^3
	KRF-BS2-U1416	1.5×10^5	5.0×10^2	7.2×10^5
	KRF-BS3-U2022	1.2×10^4	$<1.0 \times 10^2$	3.1×10^4

* Phenanthrene-Toluene

APPENDIX D

Science Applications International Corporation
An Employee-Owned Company

March 21, 1994

Mr. Clif Blanchard, P.E.
Brown & Root Environmental
800 Oak Ridge Turnpike, Suite A-600
Oak Ridge, TN 37830

Re: EPA Contract No. 68-C0-0048, WA 0-49
SAIC Contract No. 01-0832-07-1123-xxx

Dear Mr. Blanchard:

Enclosed are the results of groundwater sampling conducted on January 14-19, 1994 at Kelly AFB. These data have not been through the complete quality control review process and should be considered draft.

I have also enclosed an agenda for the March 31st Visitor's Day for the KAI radio frequency heating process. Please note the Brown & Root representative will speak between 9:40 and 10:00.

If you have any questions or comments, please call be at (513) 723-2600, ext. 2608.

Sincerely,

SCIENCE APPLICATIONS INTERNATIONAL CORPORATION

Peggy Groeber

Margaret M. Groeber

MMG/kml

Enclosure

cc: C. Dial, SAIC
L. Drees, SAIC

s9b:blanchard.ltr

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Other SAIC Offices: Albuquerque, Boston, Colorado Springs, Dayton, Huntsville, Las Vegas, Los Angeles, McLean, Oak Ridge, Orlando, Palo Alto, Seattle, Tucson

DRAFT

Results of groundwater samples from SAIC-KAI project

The following summarizes the results from the groundwater samples submitted to Radian for analysis. The sampling dates were 1/14/94, 1/18/94 and 1/19/94. Attached to each SAIC result summary and critique, are the actual lab summary sheets and any comments the lab had for the analysis. Specific comments concerning the individual groundwater samples appear as separate line items in these comments.

The SAIC summary contains the results that are considered to be usable. Reasons that some results appear in the laboratory summary sheets but not on the SAIC summary sheet is discussed following each sample.

DRAFT

Sample ID: KRF-10-GW114

Lab IDs: 9401253-14A (TRPH)
9401254-11A (Volatiles)
9401255-10A (Semi-volatiles)

Test Parameter	Result
TRPH	4.92 mg/L
Volatiles (all results are as ug/L)	
Acetone	61.9
Benzene	782
Chlorobenzene	25,500
Trans-1,2-Dichloroethene	14.0
Methyl Ethyl Ketone	16.4
4-Methyl-2-Pentanone (MIBK)	11.5
Toluene	51.2
Vinyl Chloride	28.0
Semi-volatiles (all results as ug/L)	
2,4-Chlorophenol	36.3
2-Chlorophenol	193
1,2-Dichlorobenzene	11,200
1,3-Dichlorobenzene	760
1,4-Dichlorobenzene	2160
2-Methylnaphthalene	16.2
Naphthalene	121
Phenol	22.3
1,2,4-Trichlorobenzene	51.4

There is no concern about the TRPH result.

Concerning the volatile results, the laboratory raw data sheets have results for ethylbenzene and xylene as 101 ppb and 276 ppb respectively. The reasons that they are not included are as follows. First, the internal standard used to quantitate these compounds did not pass QC requirements. This is also the reason the one surrogate compound was out of limits (see lab comments). Secondly, the sample was diluted and rerun, but the dilution results do not match up with the undiluted sample. These two compounds are probably present since they appear in amounts well over the detection limits. The actual result can only be guessed at from the lab data presented. Any other results that appear in the raw data sheets, but do not appear in the SAIC summary, were judged to be too near detection limits to be reliable.

For the semi-volatile analysis of this sample, one of the six surrogate compounds (nitrobenzene-d5) added prior to sample extraction did not pass QA/QC requirements. The lower limit for recovery of this compound is 59%. Analysis of the sample and a rerun of the sample yielded 56% and 58%. This is not cause to question the validity of the results for this sample. Any other results that appear in the raw data sheets, but do not appear in the SAIC summary, were judged to be too near detection limits to be reliable.

Sample ID: KRF-09-GW118

DRAFT

Lab IDs: 9401310-11A (TRPH)
9401311-06A (Volatiles)
9401312-05A (Semi-volatiles)

Test Parameter	Result
TRPH	0.834 mg/L
Volatiles (all results are as ug/L)	
Benzene	596
Chlorobenzene	12,000
Ethylbenzene	91.9
Toluene	5.65
Vinyl Chloride	10.2
Xylenes	12.0
Semi-volatiles (all results as ug/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

There is no concern about the TRPH result.

Concerning the volatile results, one of the three surrogate compounds (bromofluorobenzene) added to the sample prior to analysis exhibited high percent recovery. The upper acceptable limit is 115%, and the sample had a recovery of 130% for this compound. Since the rest of the QA for the analysis was acceptable, the results are judged to be usable. Any other results that appear in the raw data sheets but do not appear in the SAIC summary were judged to be too near detection limits to be reliable.

There are no concerns with the semi-volatile analysis of this sample.

DRAFT

Sample ID: KRF-DW02-GW119

Lab IDs: 9401349-05A (TRPH)
9401350-05A (Volatiles)
9401351-04A (Semi-volatiles)

Test Parameter	Result
TRPH	267 mg/L
Volatiles (all results are as ug/L)	
Chlorobenzene	15,500
Semi-volatiles (all results as ug/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

There is no concern about the TRPH result.

Concerning the volatile results, the only usable result is chlorobenzene. The laboratory only analyzed a dilute portion of this sample. This dilution may have brought other compounds that were present to below detectable levels. The laboratory states in the comment section that the sample had a strong "fuel" odor. It is assumed the laboratory did not want to damage their analytical instrumentation by analyzing the sample undiluted. Other compounds that appear at elevated levels are methylene chloride and carbon disulfide. These compounds were also found in the laboratory and field blanks for this day. After this is accounted for, the results become too close to the detection limits of the analysis.

For the semi-volatile analysis of this sample, one of the six surrogate compounds (2,4,6 Tribromophenol) added prior to sample extraction did not pass QA/QC requirements. The upper limit for recovery of this compound is 123%. Analysis of the sample yielded 151%. Since all other QA criteria for this analysis were acceptable, the results are considered usable. Any other results that appear in the raw data sheets, but do not appear in the SAIC summary, were judged to be too near detection limits.

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