

United States Air Force Environmental Restoration Program



Handbook for Remediation of Petroleum-Contaminated Sites (A Risk-Based Strategy)

Prepared For

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EXECUTIVE SUMMARY

The Air Force is responsible for thousands of sites throughout the United States and abroad that are contaminated with petroleum hydrocarbons such as jet fuel, diesel fuel, gasoline, and heating oil. Despite significant improvements in fuels management over the past 20 years, equipment failures and human error will continue to create new spills which may require remediation. The purpose of this handbook is to provide Air Force environmental managers and their supporting technical specialists with a comprehensive strategy for cost-effectively cleaning up soils and groundwater contaminated by petroleum releases. The original *Air Force Handbook for Remediation of Petroleum Contaminated Sites*, which was published in 1993, has been updated to include the most recent advances in site investigation techniques and remedial approaches and technologies. In addition, since publication of the 1993 handbook, positive regulatory changes have taken place as the United States Environmental Protection Agency (USEPA) and a majority of state regulatory agencies have adopted more flexible, risk-based regulations for petroleum release sites. In addition, many states now recognize natural attenuation as a viable treatment alternative for petroleum-contaminated groundwater. These regulatory changes have had significant impacts on the remediation process, and have been fully incorporated into this new handbook.

This document provides RPMs with answers to many of the common questions they will face while developing a remediation or closure plan for a petroleum spill site:

- Is the existing site characterization adequate to make a remedial decision?
- Can the site be placed in a closure status because no potential pathways exist for human or ecological exposure?
- What role is natural attenuation playing in site remediation and is it sufficient to eliminate future risk?

- Can the risk-based corrective action (RBCA) process be applied to speed up the site closure process?
- If significant exposure pathways exist, what remedial technologies are available (and how will you select the best technology)?
- How do you work with your regulator(s) and other interested parties to gain their approval of a site closure plan?

The handbook is “risk-based” because it focuses on reducing unacceptable risks at contaminated sites. Several approaches are described that include risk management methods which use land use controls to isolate contaminants from human contact and long-term monitoring to verify that natural attenuation is reducing future risk. More traditional risk evaluation methods are also presented which use generic or site specific exposure assumptions to develop risk-based cleanup objectives. Several case studies are provided to illustrate how various combinations of land use control, site-specific risk analysis, natural attenuation, and focused source reduction technologies have been used to obtain risk-based site closures agreements at Air Force sites across the United States. Special emphasis is given to topics such as site characterization, exposure pathways analysis, documentation of natural attenuation and the selection of cost-effective source reduction technologies. This handbook provides expanded technical guidance on risk-based remedial approaches by referencing site remediation protocols and technologies developed by the Air Force Center for Environmental Excellence (AFCEE) and other Air Force agencies. The handbook is intended to streamline the remediation process and to act as an umbrella document that directs the reader to specific references and to AFCEE protocols that provide more detailed information on each step of the process.

Every attempt has been made to establish this handbook on state-of-the-art procedures and technologies that are generally accepted by USEPA and state regulators. However, to avoid “false starts” and regulatory delays, you should identify which regulatory agency needs to be involved in your project, and include their input early in

your planning efforts. Other factors such as the appropriate funding source for remedial activities and the requirements for data quality need to be considered in the early planning phase of your project.

KEY ELEMENTS OF THE AIR FORCE APPROACH

In an effort to reduce the cost and time of cleaning up fuel-contaminated sites, the Air Force has developed a streamlined remediation approach that is comprised of five key elements or “tools”, many of which have been described in previous protocols and reports. These tools include:

- Maximum Use of Land Use Controls To Eliminate Potential Exposure
- Promotion of Chemical-Specific Cleanup Standards
- Improved Site Characterization Methods
- Scientific Documentation of Natural Attenuation, and
- Cost-Effective Technologies for Contaminant Source Reduction

The coordinated use of these tools will result in more achievable cleanup goals and the maximum use of natural attenuation, bioventing and other cost-effective cleanup techniques. This handbook is intended to complement the Air Force Relative Risk site prioritization system by providing installation and MAJCOM environmental managers with a process for obtaining site closures at low-risk sites so that limited resources can be focused on high risk sites.

Maximum Use of Land Use Control To Eliminate Exposure

The majority of Air Force petroleum contaminated sites are located in industrial areas with minimal contact between contaminated media and human or ecological receptors. Based on studies at literally thousands of fuel spill sites (Section 1.1), there is a growing consensus that natural attenuation processes have already contained most plume migration and will eventually remediate petroleum impacted groundwater. With

additional controls such as excavation restrictions, most small fuel spill sites can be placed in a "managed risk" closure status without additional studies or engineered remediation.

Chemical-Specific Cleanup Standards

Although most fuels, including JP-4 and JP-8 jet fuel, contain several hundred hydrocarbon compounds, a relatively small number of these compounds are known carcinogens or are highly toxic to humans. Once chemicals of concern are identified in the site screening process, the traditional risk-based approach focuses site characterization, fate and transport evaluations, risk exposure calculations and technology selection to specifically address these compounds. Aromatic hydrocarbons such as the benzene, toluene, ethylbenzene, and xylene (BTEX) are typically identified as fuel hydrocarbon contaminants of concern. Because of their volatility and relatively high water solubility, BTEX compounds are among the most mobile fuel compounds and can be rapidly transported through the soil and groundwater. The risk-based approach for remediation of fuel sites is focused on limiting the movement and reducing the concentration of these compounds in the environment.

Improved Site Characterization Methods

The third element of the Air Force risk-based remediation approach has been the development of accurate and inexpensive site characterization tools. Site remediation cannot proceed without some knowledge of the source of contamination, the concentration of contaminants in the soil, soil gas, and groundwater, and the three-dimensional extent of contaminant migration. In addition to these standard site characterization objectives, soil and groundwater sampling and analytical methods are now available to determine the contribution of natural biogradation processes and the rate at which these processes are destroying contaminants and reducing risk at the site. Low-cost site investigation tools such as cone penetrometers, soil gas and groundwater screening probes, and field analytical methods have been developed to help pinpoint the

source and extent of contamination and to prepare for site remediation. This “observational approach” to site investigation is described in Appendix B.

Scientific Documentation of Natural Attenuation

Perhaps the most significant remediation breakthrough in the past 5 years has been the growing evidence that natural biodegradation is a major factor in the reduction of contaminants and risk at fuel-contaminated sites. The Air Force is a national leader in the development of innovative field sampling methods, groundwater model development (such as BIOSCREEN and BIOPLUME III), and in documenting case studies that support natural attenuation as a viable method of site remediation. The Air Force has partnered with USEPA in the development of both bioventing and natural attenuation protocols which have become a standard reference in the environmental engineering community. Appendix C describes how the contribution of natural attenuation can be determined at each site and how natural processes can be factored into the risk evaluation process.

Low-Cost Technologies for Source Reduction

At sites with significant free product or high concentrations of contaminants in the soil or groundwater, natural attenuation processes often are too slow to reduce risk within a reasonable time frame. At these sites, a more active source reduction technology will be required to reduce the mass of contaminants and to enhance and accelerate their natural destruction. Several cost-effective technologies have been developed and widely tested by the Air Force to meet the need for source reduction. The Air Force bioventing initiative demonstrated that bioventing technology was effective at reducing BTEX concentrations in the soil by over 90 percent when applied for 1 year at over 125 test sites. Similarly, bioslurping technology is capable of improving the rate of free product recovery at many sites where other technologies have failed. A variety of vapor treatment technologies have been successfully demonstrated by the Air Force at sites where soil vapor extraction is required. Section 3 and

Appendix E describe several proven technologies for fuel remediation and how to select the most appropriate technology for your site.

BENEFITS OF THE RISK-BASED APPROACH TO REMEDIATION

There are several benefits associated with the use of a risk-based remediation approach, and these benefits are illustrated throughout this handbook. In overview, these benefits include:

- A focus on only those contaminants that pose a potential risk to human or ecological receptors. The premise of risk-based remediation is that the decision to remediate any petroleum release site should be based on the actual or potential risk posed by site-specific contaminants to human and ecological receptors. This is an intentional move away from the use of cleanup standards for total petroleum hydrocarbons (TPH), which is not the true “risk driver” at petroleum release sites.
- More flexible and realistic cleanup standards based on actual land use (which on most bases is commercial or industrial) rather than conservative “residential” scenarios. Flexibility is available to choose between a more rapid and costly remediation, which will allow more immediate, unrestricted land use, and a less expensive natural attenuation option, which requires some long-term restrictions on land and groundwater use.
- A streamlined process. The Air Force risk-based remediation process is designed to integrate the site investigation, risk analysis, and feasibility study into a single effort, rather than conducting each of these in separate phases. Several risk-based site demonstrations, including two large petroleum, oil, and lubricant (POL) tank farm facilities, have progressed from site investigation to an approved site closure agreements in a period of less than 3 years.
- Significant cost and time savings have been demonstrated at Air Force sites which have entered into risk-based site closure agreements. Cost savings of 40 to 60

percent have been realized when compared to the more traditional Installation Restoration Program process of site investigation, risk assessment, feasibility study, remedial design and remedial action. Typical timeframes for completing the standard IRP process have ranged from 5 to 7 years at a cost of \$500,000-\$700,000 for a typical Air Force gasoline station or JP-4 pumphouse to obtain a site closure agreement. Using the risk-based approach, costs of \$200,000 to \$300,000 have been consistently demonstrated in project timeframes of less than 3 years. An important objective of this handbook is to provide each Air Force environmental manager with the tools to achieve this level of time and cost savings at existing and future fuel spill sites.

TABLE OF CONTENTS

	Page
EXECUTIVE SUMMARY	ES-1
ACRONYMS AND ABBREVIATIONS	iv
ACKNOWLEDGEMENTS.....	vii
SECTION 1 - INTRODUCTION.....	1-1
1.1 Recent Trends in Fuel Spill Remediation	1-1
1.1.1 AFCEE Initiatives.....	1-1
1.1.2 National Research Council -Alternatives for Groundwater Cleanup.....	1-2
1.1.3 ASTM Risk-Based Corrective Action (RBCA) Standard.....	1-2
1.1.4 Lawrence Livermore National Laboratory (LLNL) Study	1-2
1.1.5 Texas Plume Study	1-3
1.1.6 Regulatory Progress.....	1-3
1.2 Organization of The Handbook	1-4
SECTION 2 - SITE CLOSURE STRATEGIES	2-1
2.1 Requirements for Site Screening	2-2
2.1.1 Review of Available Site Data	2-2
2.1.2 Determining Current and Future Land Use.....	2-4
2.1.3 Developing a Conceptual Site Model (CSM)	2-6
2.1.4 Estimating Natural Attenuation in Soil and Groundwater	2-10
2.1.4.1 Natural Attenuation in Soil.....	2-10
2.1.4.2 Natural Attenuation in Groundwater	2-11
2.1.5 Determining The Applicable Regulatory Framework.....	2-12
2.1.6 Selecting a Site Closure Approach	2-13
2.2 Managing Risk Through Pathway Elimination	2-14
2.2.1 Completing a Pathway Analysis	2-14
2.2.2 Establishing Institutional Controls.....	2-16
2.2.3 Evaluating Source Reduction.....	2-17
2.2.4 Using Natural Attenuation for Plume Containment	2-18
2.3 Remediation to Risk- Based Cleanup Goals.....	2-19
2.3.1 Fundamentals of Risk-Based Corrective Actions (RBCA)	2-20
2.3.1.1 Using Tier 1 Generic Screening Levels.....	2-20
2.3.1.2 Developing Tier 2 Site-Specific Cleanup Goals	2-21
2.3.2 Attaining Cleanup Goals Using Natural Attenuation.....	2-23
2.3.3 Attaining Cleanup Goals Through Source Reduction	2-24
2.4 Modified Site Closure Strategies.....	2-25
SECTION 3 - EVALUATING SOURCE REDUCTION TECHNOLOGIES	3-1
3.1 Determining The Need for Source Reduction	3-1
3.1.1 The No Source Removal Option.....	3-1
3.1.2 The Engineered Source Reduction Option	3-2

TABLE OF CONTENTS (Continued)

	Page
3.2 Identifying The Remediation Target	3-4
3.3 Source Reduction Technology Selection Process	3-6
3.3.1 Technologies With Widespread Application.....	3-7
3.3.2 Technologies With Limited Application.....	3-16
3.4 Remediation Time and Cost Estimates.....	3-22
3.5 Pilot Testing.....	3-22
SECTION 4 - PLUME REMEDIATION	4-1
4.1 Review of Regulatory Options	4-1
4.2 Plume Containment	4-2
4.2.1 Potential Applications	4-2
4.2.2 Demonstrating Plume Stability or Limited Migration.....	4-3
4.2.3 Institutional Controls for Groundwater.....	4-5
4.2.4 Establishing a Plume Containment Monitoring Strategy	4-6
4.2.4.1 Locating Point-of-Action Wells	4-6
4.2.4.2 Monitoring Frequency	4-7
4.3 Remediating Plumes to Cleanup Goals	4-8
4.3.1 Potential Applications	4-8
4.3.2 Using Natural Attenuation to Achieve Risk-Based Cleanup Goals	4-9
4.3.3 Combining Natural Attenuation and Engineered Remediation	4-10
4.4 Establishing a Remediation Monitoring Plan	4-11
4.4.1 Primary Components of a Groundwater Monitoring Plan.....	4-11
4.4.2 Optimizing Long-Term Monitoring Plans	4-13
SECTION 5 - DOCUMENTATION.....	5-1
5.1 Gaining Regulatory Acceptance.....	5-1
5.2 Preparing a Work Plan	5-2
5.3 Regulatory Participation In Risk Evaluation.....	5-4
5.4 Preparing a No Further Action Closure Document.....	5-5
5.5 Preparing The Remedial Action Plan	5-5
5.5 Effective Presentations	5-9

APPENDICES

- A - Risk-Based Case Studies
- B - Site Characterization
- C - Documenting Natural Attenuation
- D - Developing Risk-Based Cleanup Goals
- E - Remediation Time and Cost Estimates/Pilot Testing Procedures
- F - Overview of Applicable Regulations
- E - Recommended References and Point-of-Contact

TABLE OF CONTENTS (Continued)

LIST OF TABLES

No.	Title	Page
3.1	Technologies for Remediation of Petroleum-Contaminated Sites	3-9
4.1	Historical BTEX Concentrations, KC-135 Site, Wurtsmith AFB.....	4-5

LIST OF FIGURES

No.	Title	Page
2.1	Basic Risk Evaluation Model.....	2-2
2.2	Limited Industrial Exposure Site Model.....	2-7
2.3	Multiple Pathways Conceptual Site Model.....	2-9
2.4	Air Force Risk-Based Remediation Approach.....	2-15
3.1	Flow Chart for Remediation Technology Selection	3-8
4.1	Minimum Monitoring Well Layout for Petroleum-Contaminated Sites.....	4-6
4.2	Typical Monitoring Well Layout for Large Plumes.....	4-14

ACRONYMS AND ABBREVIATIONS

AAR	American Association of Railroads
AFB	Air Force Base
AFCEE	Air Force Center for Environmental Excellence
ASTM	American Society for Testing and Materials
bgs	below ground surface
BRA	baseline risk assessment
BRAC	Base Realignment and Closure
BTEX	benzene, toluene, ethylbenzene, xylenes
CAP	corrective action plan
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act
cfm	cubic feet per minute
CFR	Code of Federal Regulations
COPC	chemical of potential concern
CPT	cone penetrometer testing
CSM	conceptual site model
DAF	dilution/attenuation factor
DERP	Defense Environmental Restoration Program
DO	dissolved oxygen
DoD	Department of Defense
DQO	data quality objective
EE/CA	engineering evaluation/cost analysis
FS	feasibility study
gpd	gallons per day
ΔG_r°	standard (Gibbs) free energy
HDPE	high-density polyethylene
HSSM	Hydrocarbon Screening Spill Model
HSWA	Hazardous and Solid Waste Amendments of 1984
ID	inside-diameter
IDW	investigation derived waste
IRP	Installation Restoration Program
L	liter
LEL	lower explosive limit
LNAPL	light nonaqueous-phase liquid
LTM	long-term monitoring
LTMP	long-term monitoring plan
LUFT	leaking underground fuel tank
MAP	management action plan
MCL	maximum contaminant level
MDL	method detection limit
μg	microgram
$\mu\text{g}/\text{kg}$	microgram per kilogram

µg/L	microgram per liter
mg	milligram
mg/kg	milligrams per kilogram
mg/L	milligrams per liter
mg/m ³	milligrams per cubic meter
mm Hg	millimeters of mercury
MOC	method of characteristics
MOGAS	motor gasoline
NAPL	nonaqueous-phase liquid
NCP	National Contingency Plan
NFRAP	no further response action plan
NOAA	National Oceanographic and Atmospheric Administration
NOEL	no-observed-effect level
NPL	National Priorities List
OD	outside-diameter
OSHA	Occupational Safety and Health Administration
OSWER	Office of Solid Waste and Emergency Response
PAH	polycyclic aromatic hydrocarbon
PEL	permissible exposure limit
POA	point-of-action
POC	point-of-compliance
POL	petroleum, oil, and lubricant
ppmv	parts per million per volume
psi	pounds per square foot
PVC	polyvinyl chloride
QA	quality assurance
QC	quality control
RAP	remedial action plan
RBCA	risk-based corrective action
RBSL	risk-based screening level
redox	reduction/oxidation
RFI	RCRA facility investigation
RI	remedial investigation
RME	reasonable maximum exposure
RPM	remedial project manager
SAP	sampling and analysis plan
SARA	Superfund Amendments and Reauthorization Act
scfm	standard cubic feet per minute
SPCC	spill prevention, control, and countermeasures
SSL	soil screening level
SSTL	site-specific target level
SVE	soil vapor extraction
SVOC	semivolatile organic compound
TC	toxicity characteristic

TCLP	toxicity-characteristic leaching procedure
TMB	trimethylbenzene
TOC	total organic carbon
TPH	total petroleum hydrocarbons
TRPH	total recoverable petroleum hydrocarbons
TVH	total volatile hydrocarbons
TVPH	total volatile petroleum hydrocarbons
TWA	time-weighted-average
UCL	upper confidence limit
US	United States
USGS	US Geological Survey
UST	underground storage tank
VOCs	volatile organic compounds

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SECTION 1

INTRODUCTION

1.1 RECENT TRENDS IN FUEL SPILL REMEDIATION

Since 1993, significant regulatory and scientific advancements have been made in the characterization, assessment, remediation, and regulation of petroleum contaminated sites. The growing acceptance of site specific cleanup goals and scientific evidence supporting the natural attenuation alternative have led to less intrusive and more cost-effective methods of remediating and closing these sites. The purpose of this section is to provide an overview of some of the significant studies and events which are reshaping the way that we view petroleum spills, and to provide the reader with an overview of how this handbook can be used to take maximum advantage of this shift in remediation philosophy.

1.1.1 AFCEE Initiatives

In 1992, AFCEE began two major technology demonstration programs to encourage the widespread application of bioventing and natural attenuation on over 50 Air Force installations in the United States. The successful demonstration of bioventing at over 125 sites and natural attenuation at over 50 sites located across the nation (including Alaska) propelled international interest in the use of these simple, cost-effective methods of reducing the risk associated with BTEX compounds. In 1994, AFCEE initiated a risk-based site closure initiative which combined the merits of natural attenuation, bioventing and site-specific risk-based cleanup criteria to streamline the site closure process. This handbook summarizes the "lessons learned" from this project and similar projects being completed by other organizations. Case studies are presented in Appendix A demonstrating how risk-based closure agreements have been negotiated at several Air Force sites.

1.1.2 National Research Council -Alternatives for Groundwater Cleanup

In 1993, a committee of international experts in groundwater remediation assembled for the purpose of reviewing the progress of groundwater pumping and treatment at dozens of active remediation sites. They concluded that restoration of groundwater to drinking water levels was impractical and technically infeasible at many sites. In addition they recommended that state and federal regulations allow greater flexibility in addressing site-specific risks, rather than setting unrealistic cleanup goals that have little to do with actual risk reduction.

1.1.3 ASTM Risk-Based Corrective Action (RBCA) Standard

The risk-based initiative picked up additional momentum when the American Society for Testing and Materials (ASTM) (1995) published RBCA guidance for petroleum-contaminated sites. This guidance was developed to provide a more consistent and rational decision-making process for the remediation of petroleum-contaminated sites, and specifically the thousands of contaminated gasoline stations across the United States. A three-tiered approach was designed to provide the site owner and regulatory agencies with a more consistent method of classifying sites as to the urgency and scope of cleanup required at each site. With the sponsorship of the petroleum industry, RBCA training was offered to every state underground storage tank (UST) group in the nation. This training has resulted in many new state regulations which incorporate all or part of the ASTM standard.

1.1.4 Lawrence Livermore National Laboratory (LLNL) Study

In June of 1994, the State of California Water Resources Control Board (SWRCB) retained LLNL and the University of California (UC) to study the cleanup of leaking underground fuel tanks (LUFTs) in the state. The study consisted of data collection and analysis of over 1,200 LUFT case studies located throughout the state (Rice et al, 1996). The study focused on the occurrence of dissolved benzene plumes and how these plumes have migrated and decreased in concentration over time. The study concluded that 90 percent of the benzene plumes were less than 260 feet long and were

either stable or shrinking in size. The study also concluded that 75 percent of the plumes were confined to shallow aquifers and that a very small percentage of these 1,200 sites actually posed a risk to drinking water supplies or human or ecological receptors. As a follow on to this study, 10 Department of Defense (DOD) sites in California were identified for more detailed study of natural attenuation and risk-based closure potential.

1.1.5 Texas Plume Study

In 1997, the University of Texas published a detailed statistical analysis of 605 sites with petroleum contaminated groundwater. The results fully supported the findings of the California LLNL study. Benzene plumes of less than 250 feet were observed at 75 percent of the sites and only 3 percent of the plumes were determined to be increasing in length. Although 60 percent of the sites had public or domestic wells within a 0.5 mile radius, less than 5 percent were posing an immediate threat to public health. Natural attenuation and low aquifer permeability are effectively remediating the majority of petroleum generated groundwater plumes in this state.

1.1.6 Regulatory Progress

Beginning in the early 1990s, many states began to realize that few petroleum release sites posed an immediate risk to human or ecological receptors, and that significant private and taxpayer monies were being spent for little risk-reduction benefit. Many state UST reimbursement funds were depleted with little to show in the way of health-protective remediation. Although most UST programs allowed risk analysis to justify alternative cleanup goals, very few regulators and UST remedial managers were comfortable using the available risk assessment "tools," which were usually reserved for costly Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) investigations. In most instances, the conservative, risk-based cleanup goals were designed to protect future onsite residents, even if the current land use was industrial. Today, over 40 states have adopted some form of risk-based remediation criteria for petroleum sites. Texas and a host of other states also developed chemical

specific and less stringent standards for industrial/commercial land uses. Many states are simplifying site closure standards and requiring that the site owner manage risks through preventing contact with contaminated soil by using excavation restrictions and demonstrating plume stability through groundwater monitoring data. The AFCEE "Toolbox" has been updated to include a 1997 summary of state UST regulations.

For CERCLA and Resource Conservation and Recovery Act (RCRA) sites, the EPA has prepared a draft policy statement supporting "monitored natural attenuation" as a viable alternative for groundwater contaminants which pose no current or potential risk to human health or the environment. The EPA policy cautions that natural attenuation may not be appropriate where long-term monitoring costs exceed the cost of more active remediation.

In light of these scientific advances and state and federal recognition of natural attenuation and risk-based remediation, AFCEE has requested that all Air Force environmental managers assess the potential of the natural attenuation alternative for all sites (including non-petroleum sites) entering the feasibility study or remedial design phase. Sites with active groundwater pumping systems should be reassessed to determine if natural attenuation is a more effective long-term remediation strategy.

1.2 ORGANIZATION OF THE HANDBOOK

This handbook has been organized to provide the reader with a comprehensive strategy for completing all phases of a risk-based site remediation. The handbook has been arranged in a chronological order that matches the normal order of decision making recommended for most remediation projects. Although technical guidance is provided, this document has limited technical details and generally references supporting AFCEE technical protocols for detailed information. The handbook has been organized into five sections with six supporting appendices.

Section 1 - Introduction: Outlines the recent events leading up to the development of this handbook, the organization of this document and the benefits of implementing the Air Force's risk-based strategy for petroleum hydrocarbon site remediation.

Section 2 - Risk Management Strategies for Site Closure: Describes the essential site characterization data which must be available to make site closure decisions and outlines two primary approaches to risk-based site remediation and closure. Summarizes how natural chemical attenuation processes should be factored into remedial decisions for petroleum release sites.

Section 3 - Evaluating Source Reduction: Describes situations where source reduction technologies may not be required or beneficial. Provides information on available engineered remediation technologies, how to select the most appropriate technologies, and how they can be coupled with natural chemical attenuation to attain risk-based remediation goals.

Section 4 - Plume Management and Remediation: Provides an overview of both "monitored natural attenuation" and engineered remediation options for petroleum impacted groundwater. Information on institutional groundwater use restrictions and long-term monitoring strategies are also presented.

Section 5 - Documenting Risk-Based Closure Agreements: Provides practical suggestions for preparing and presenting effective risk-based documentation for regulatory review and approval.

Appendix A - Case Studies: Presents a series of case studies where the Air Force risk-based remediation approach has been successfully used to negotiate cost-effective closure agreements. Beginning with a simple "no further action" site closure for a heating oil spill, and progressing to a more complex remediation plan for a large JP-4 tank farm, the case studies illustrate how combinations of institutional controls, natural attenuation, site-specific cleanup standards and cost-effective source reduction technologies have been used to achieve the desired level of risk reduction and to gain

approval for site closure. The case studies listed below have been organized and ordered to illustrate how increasingly complex sites can be addressed under the risk-based approach.

- Case Study A - "No Further Action" closure of a heating oil UST site - Site OT-45, Wurtsmith AFB, MI.
- Case Study B - Corrective action for a large JP-4 spill based on natural chemical attenuation, land use controls, and long-term monitoring - KC-135 Crash Site, Wurtsmith AFB, MI.
- Case Study C - Corrective action for a JP-4/gasoline release beneath a concrete aircraft apron that includes interim removal action, long-term bioventing, natural chemical attenuation, land use controls, and long-term monitoring - Site ST-27, Charleston AFB, SC.
- Case Study D - Corrective action for a JP-4 tank farm that includes a detailed risk evaluation, bioventing for source reduction, natural chemical attenuation, land use controls, and long-term monitoring - POL Area, Carswell AFB, TX.

Appendices B-G - Technical Resources: Provides additional information on site characterization, estimating natural attenuation, risk-based cleanup goals, source reduction technologies and an overview of regulatory options. Appendices include a listing of useful reference material and AFCEE technical protocols, as well as instructions on how to obtain these supporting documents.

SECTION 2

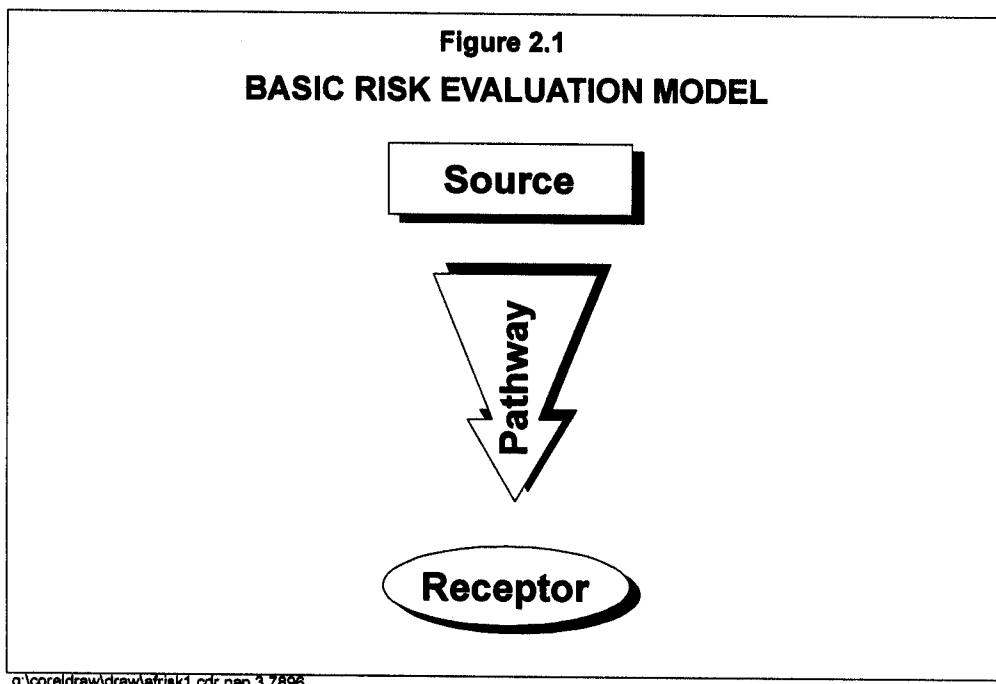
SITE CLOSURE STRATEGIES

The fundamental objective of risk-based remediation is to reduce the risk of specific chemicals to human health and to ecological receptors such as animals and plant life. This section reviews the information you will need to determine if a potential risk exists at a site, and to implement the risk-reduction strategy that can be used to move a site toward final closure. The strategy that is selected will depend upon such factors as the magnitude of contamination, current and future land use, evidence of natural attenuation, potential for human or ecological exposure, and the applicable regulatory framework. The purpose of this section is to provide Air Force environmental managers with an overview of the initial screening data which must be collected to evaluate and select the most cost-effective remediation/closure strategy. A decision diagram is provided later in this section to assist in the reader in the site-specific evaluation process.

Based on conservative toxicological studies, safe exposures to many chemical compounds such as BTEX have been determined. Chemical exposure is generally based on the average intake of a certain mass of chemical per day. USEPA has established different human exposure scenarios for different land uses. For example, the residential scenario generally assumes a 24-hour-per-day exposure, while the industrial scenario assumes an 8-hour-per-day exposure for each worker. From these conservative exposure scenarios, generic screening levels have been established to provide safe exposure concentrations for a variety of different chemicals. For any chemical risk to exist three elements must exist at the site (Figure 2.1):

- A chemical source that exceeds the safe exposure concentration;

- A completed pathway for the chemical to enter the receptor; and
- A human or ecological receptor available for chemical contact.



2.1 REQUIREMENTS FOR SITE SCREENING

2.1.1 Review of Available Site Data

At most sites, site data from past investigations is available and very useful in completing an initial risk-based screening. Historical data are particularly valuable in establishing evidence of natural attenuation processes which may be limiting contaminant migration and reducing long-term risks. Site contaminant data should be organized by environmental medium (e.g. soil, soil gas, groundwater, etc.) and arranged in a tabular format. A site map should be available showing sampling locations, historical BTEX plumes, and key land use and natural features. Appendix B provides additional guidance on collecting and organizing site characterization information. Existing data should be sufficient to answer the following key questions:

- Where is the primary source of the contamination and has it been removed or the leak stopped? (See note)

- Is the date of release known or was it a long-term leak?
- What media have been impacted (soil, groundwater, soil gas, surface water)?
- Are there any immediate risks to human health or the environment (see Appendix D)?
- Are there any potential risks due to soil vapors, excavation, groundwater migration to drinking water wells or surface water (see Appendix D)?
- Does free product remain at the site (based on existing monitoring wells)?
- Has the geology and soil stratigraphy been defined?
- Have the groundwater flow direction and gradient been defined?
- Has the full extent of soil and groundwater contamination been defined?
- Does the groundwater plume appear to be migrating or stable based on historical data (see Appendix C)?
- Have basic geochemical parameters (dissolved oxygen, ferrous iron, sulfate and methane) been collected and plume migration estimated using BIOSCREEN (see Appendix C)?

If any of these questions can not be answered, additional site characterization will likely be required before a risk-based site closure can be pursued. Site characterization methods, including the use of low-cost sampling devices, are described in greater detail in Appendix B. Make a list of any unanswered questions and continue reading Section 2 to complete your list of “data gaps”.

Note on Source Identification. Because many fuel-contaminated sites are located in active fuel handling areas, the possibility of continuing leaks must be thoroughly investigated. Regular tank and pipeline testing will be required to insure that a significant ongoing leak is not contributing to soil and groundwater contamination. Your MAJCOM Liquid Fuels manager should be consulted to determine the most appropriate leak testing method for your system. The recent move towards replacement of underground piping with aboveground piping should greatly reduced undetected leaks, however, small leaks are inevitable in any large fuel handling facility. Often these small leaks are naturally attenuated before contaminants migrate from the site.

2.1.2 Determining Current and Future Land Use

An equally important aspect of the initial site evaluation is an understanding of current and future land use at the site. A site walk should be scheduled with the facility manager to determine the type of buildings constructed near the site and the frequency and type of human activity. Because risk-based remediation methods rely on a clear understanding of how humans could be exposed to chemicals (exposure pathways), it is essential to have a complete knowledge of the current land use and potential land use changes.

Most Air Force fuel systems are located in the industrial or commercial areas of the base. On-site workers typically work 8 to 12 hour shifts inside buildings or outside, working on aircraft or support equipment. Excavation in contaminated soils is generally restricted to short-term utility repairs. Most buildings are constructed on abovegrade concrete slabs. With the exception of missile facilities, few Air Force industrial buildings have basements which could be directly impacted by contaminated soil and soil gas. As a rule, current land use near fuel spills is generally industrial or commercial in nature with little chance of direct exposure to contaminated soil, soil gas, or groundwater. This isolation of workers from site contamination (no exposure pathways) is an important element of the Air Force risk-based remediation strategy.

On active Air Force installations, future land use is specified in the Base Master Plan. This document is maintained by the Base Civil Engineer, and specifies areas of the base for various land uses such as flightline/industrial, warehousing/storage, administration, community services, and residential housing and dormitories. Land use within the flightline/industrial area rarely changes because of the incompatibility of other land uses with flightline noise and aircraft support activities. Most fuel-contaminated sites should remain in the flightline/industrial land use category. Check the Base Master Plan to ensure that no significant change in land use or new construction is planned at the site.

The greatest potential for exposure to fuel contaminated soil and groundwater will occur during new building construction or utility repairs or replacement. It is important that the supervisors of utility shops and base construction planners be informed of the known areas of fuel contamination so that any excavation in these areas can be completed with careful air monitoring and any contact with fuel vapors and fuel residuals can be avoided or minimized.

On installations that are scheduled for closure or realignment, the question of future land use becomes more critical. While most base flightline and industrial areas on closure bases will remain in this land use, formal deed or lease restrictions must be in place to ensure that the new landowner (private or public) understands the extent of remaining fuel contamination and the need to restrict certain future activities or land uses. In general, Air Force Base Realignment and Closure (BRAC) officials should seek risk-based closures of fuel contaminated sites which make maximum use of deed restrictions to minimize the potential for future human exposure to contaminants. The BRAC Environmental Program Fact Sheet (DoD Policy on Institutional Controls) provides an overview of institutional controls and how they can be applied during BRAC land transfers. This guidance is available on the DoD BRAC Environmental Homepage at <http://www.dtic.mil/envirodod/envbrac.mil>.

2.1.3 Developing a Conceptual Site Model (CSM)

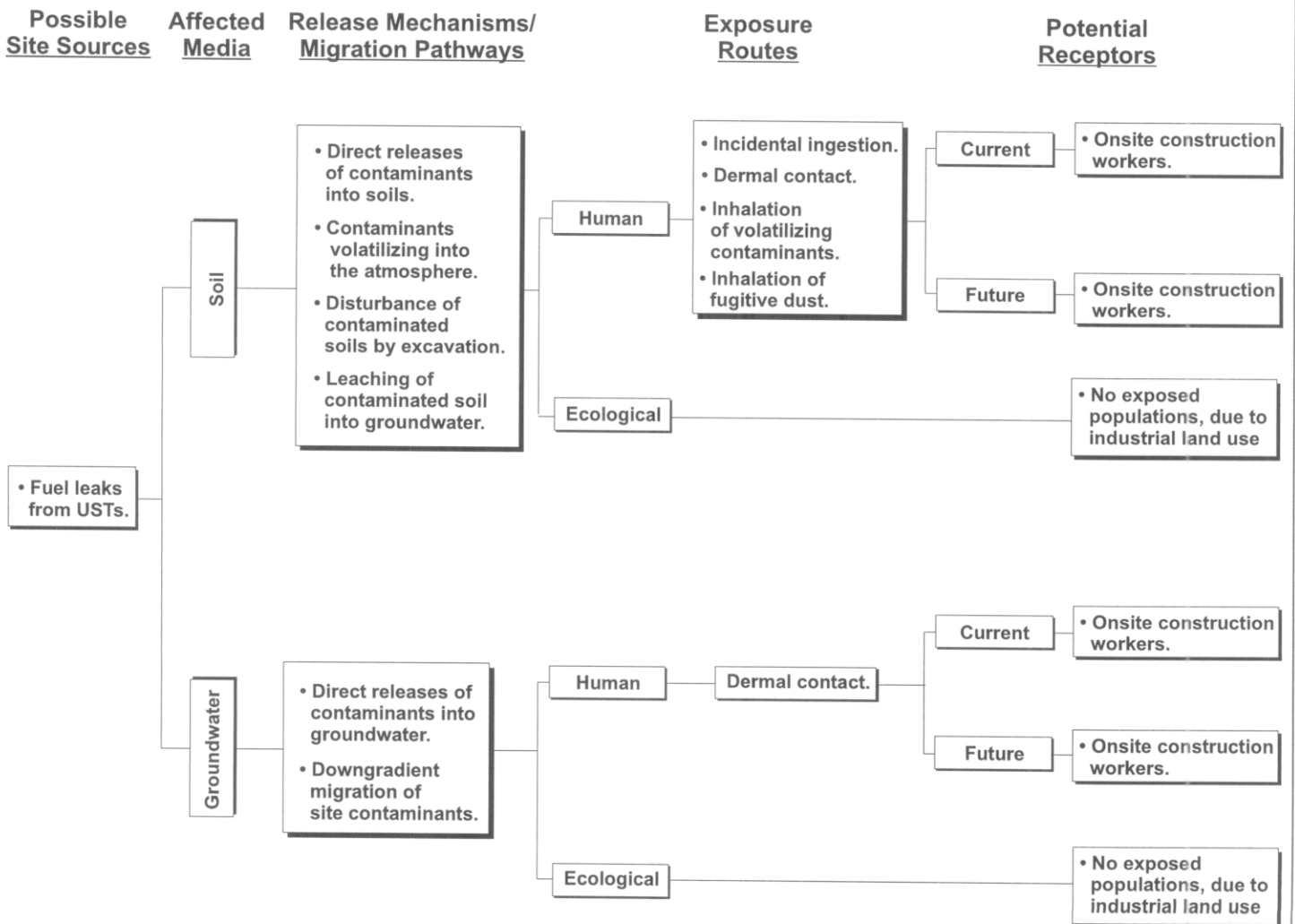
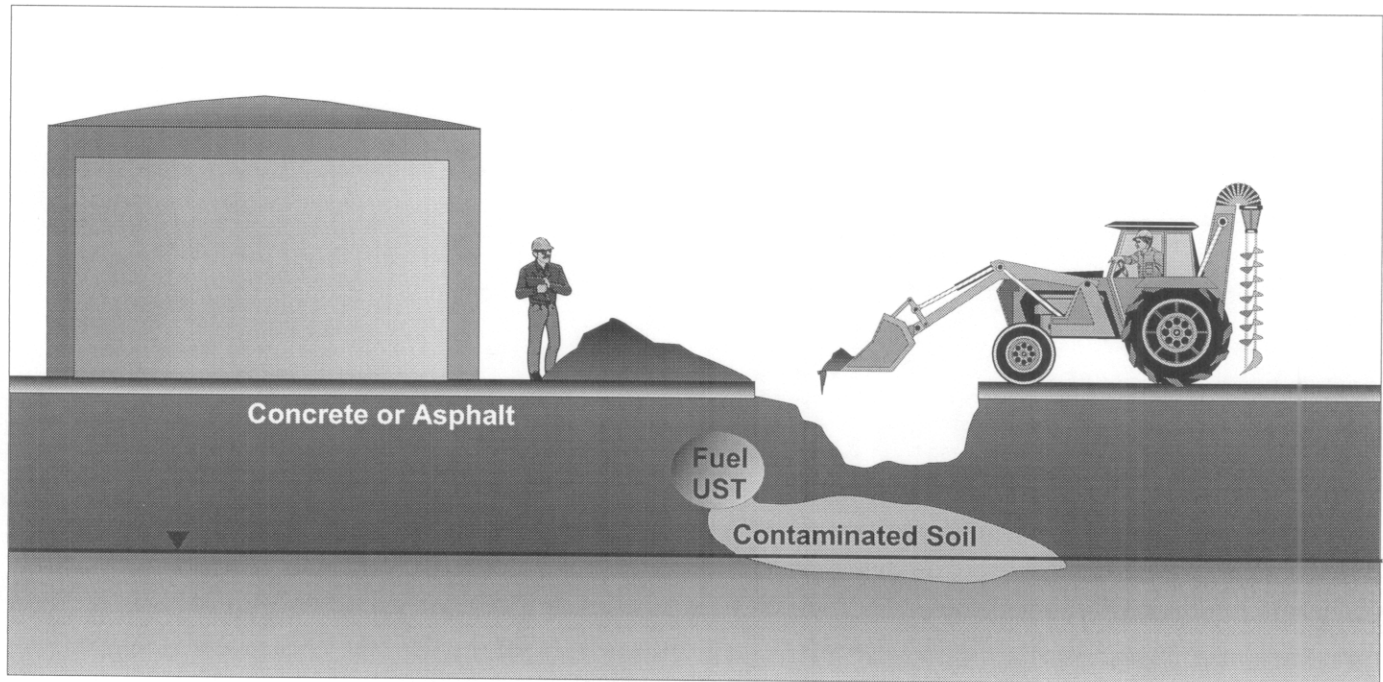
The next step of the site screening process is to develop a conceptual site model which combines available information on site contamination with information on potential human receptors based on current and future land use. Potential ecological receptors such as wildlife living in or near drainage ditches should also be included in the conceptual site model. Although the complexity of risk-based analysis will vary from one site to another and one regulatory environment to another, there are three common elements of all risk-based evaluations: a source, pathways and receptors.

If any one of these elements is absent at a site, there is no current risk. The reduction or removal of risk can be accomplished by limiting or removing any one of these three elements from the site. The goal of risk-based remediation is to find the most cost-effective method of reducing present and future risk by combining three risk reduction techniques:

1. **Chemical Source Reduction** - Achieved by natural attenuation processes over time or by engineered removals such as limited excavation, soil vapor extraction, or bioventing.
2. **Chemical Pathway Elimination** - Examples include the natural attenuation of a groundwater plume and restrictions on excavation or groundwater use to prevent onsite or offsite receptors from contacting chemicals of concern.
3. **Restrict Receptors** - Land use controls and site fencing can eliminate chemical exposure until natural attenuation or engineered remediation reduces the chemical source.

A CSM consists of three primary components that were addressed at the beginning of this Section. A source of contamination, a contaminant migration pathway or pathways from the source to receptors, and potential receptors. Figure 2.2 illustrates a CSM for a typical JP-4 UST leak in an industrial area. The primary contaminant source is the UST; the secondary source is the soil contaminated with JP-4 residuals

**FIGURE 2.2
LIMITED INDUSTRIAL EXPOSURE SITE MODEL**



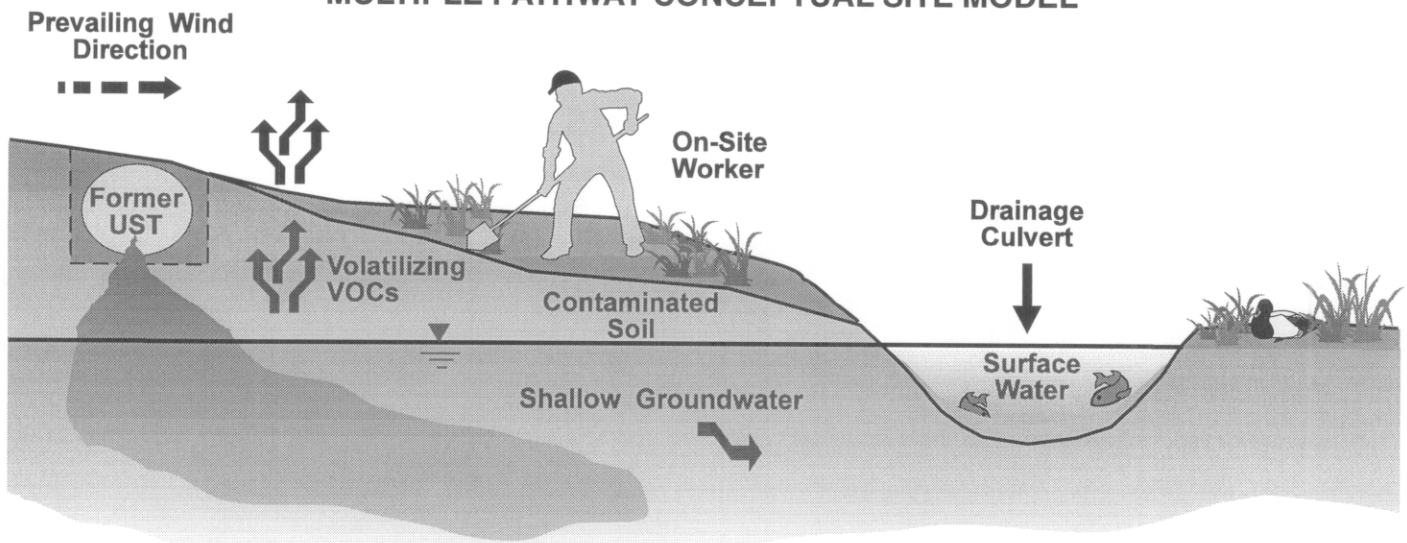
(with no remaining free product). Potential exposure pathways include soil contact, soil-vapor inhalation, or dermal contact with impacted shallow groundwater. The only potential receptor in this industrial scenario are intrusive construction or utility workers who will have a limited exposure time frame resulting in limited risk.

Figure 2.3 illustrates a CSM for leaking UST located in a more accessible commercial area such as a BX Service Station. Potential exposure pathways include soil contact or ingestion, soil vapor migration to the atmosphere, incidental contact with shallow groundwater, and direct contact or incidental ingestion of impacted surface waters. Potential receptors include both on site workers and ecological receptors in the nearby surface water. This CSM indicates a greater risk may be present at this site due to greater potential for receptors to be exposed through multiple pathways.

A site visit is required to properly complete the CSM. To be conservative, the preliminary CSM should account for all possible pathways and receptors given the current and likely future land uses. Often at military facilities scheduled for closure, the future land use may differ from the current land use. In such situations the most conservative expected land use should be used to complete the site model. Industrial or commercial land use should be assumed unless residential land use is included in a future land use plan.

In the risk-based remediation process, site characterization is used to first determine if a completed pathway exists. Existing site data should be reviewed to identify which potential pathways cannot be evaluated due to a lack of quantitative chemical data for that environmental medium. For example, one pathway that is frequently overlooked is the exposure of site workers to soil vapors during excavation activities. One common data gap is the lack of soil gas data to quantify the concentration of specific VOCs (generally BTEX). A complete CSM will help ensure that all the data required for risk evaluation are gathered in one field mobilization. Appendix B provides additional guidance on how to use the CSM to guide additional site characterization.

**FIGURE 2.3
MULTIPLE PATHWAY CONCEPTUAL SITE MODEL**



Possible Site Sources	Affected Media	Release Mechanisms/ Migration Pathways	Exposure Routes	Potential Receptors
<ul style="list-style-type: none"> Fuel leaks from transfer and supply and return pipelines. Fuel leaks from USTs. Surface spills/ overfills. 	Soil	<ul style="list-style-type: none"> Direct releases of contaminants into soils. Leaching of surface spills into subsurface soils. Surface erosion/deposition of contaminated soil by either water or wind. Contaminants volatilizing into the atmosphere. Disturbance of contaminated soils by excavation. Leaching of contaminants into groundwater. 	Human <ul style="list-style-type: none"> Incidental ingestion. Dermal contact. Inhalation of volatilizing contaminants. Inhalation of fugitive dust. 	Current <ul style="list-style-type: none"> Onsite workers. Future <ul style="list-style-type: none"> Onsite workers.
			Ecological <ul style="list-style-type: none"> Surface soil is not contaminated. 	<ul style="list-style-type: none"> No exposed populations.
			Human <ul style="list-style-type: none"> Dermal contact. 	Current <ul style="list-style-type: none"> Onsite construction workers. Future <ul style="list-style-type: none"> Onsite construction workers.
<ul style="list-style-type: none"> Fuel leaks from transfer and supply and return pipelines. Fuel leaks from USTs. Surface spills/ overfills. 	Groundwater	<ul style="list-style-type: none"> Direct releases of contaminants into groundwater. Leaching of surface spills into subsurface soils. Downgradient migration of sites contaminants. Contaminants volatilizing into vadose zone soil. Migration and discharge of contaminated groundwater into off-base surface water. 	Human <ul style="list-style-type: none"> Dermal contact. 	Current <ul style="list-style-type: none"> Onsite construction workers. Future <ul style="list-style-type: none"> Onsite construction workers.
			Ecological	<ul style="list-style-type: none"> No exposed population due to industrial land use.
			Human <ul style="list-style-type: none"> Incidental ingestion. Dermal contact. 	Current <ul style="list-style-type: none"> Onsite workers. Future <ul style="list-style-type: none"> Onsite workers.
<ul style="list-style-type: none"> Fuel leaks from transfer and supply and return pipelines. Fuel leaks from USTs. Surface spills/ overfills. 	Surface Water	<ul style="list-style-type: none"> Surface runoff of precipitation. Discharge of contaminated groundwater into surface water. Discharge of leachate into surface water. 	Human <ul style="list-style-type: none"> Incidental ingestion. Dermal contact. 	Current <ul style="list-style-type: none"> Onsite workers. Future <ul style="list-style-type: none"> Onsite workers.
			Ecological	<ul style="list-style-type: none"> BIOSCREEN predicts no migration at concentrations > surface water criteria.

2.1.4 Estimating Natural Attenuation in Soil and Groundwater

2.1.4.1 Natural Attenuation in Soil

To accurately assess the potential for soil contaminants to attenuate, many fate and transport processes must be accounted for. For example, it is important to understand the relationship between fuel residuals in the soil (sorbed, trapped and free product) and soil gas and groundwater contamination. A number of predictive models are available to estimate contaminant fate and transport and are described in Appendix C. Appendix B provides additional guidance on determining the role of biodegradation to naturally reduce the level of petroleum residuals in the soil. If possible, soil gas samples should be collected from near the center of the spill area and at several points around the perimeter of the spill. If site soil gas data indicate an abundance of oxygen (> 5 percent) in contaminated soils, it generally can be assumed that atmospheric oxygen is available to soil bacteria and these bacteria are biodegrading residual hydrocarbons. Site specific biodegradation rates can be estimated by conducting in situ respiration tests in accordance with the *Air Force Bioventing Principals and Practice Manual*. Natural biodegradation rates generally range from 1 to 10 mg TPH/kg soil/day with 4 mg/kg soil/day as an average value based on over 135 test sites nationwide (AFCEE, 1996).

For natural biodegradation to proceed in soil, the soil must be naturally aerated through simple atmospheric oxygen diffusion and barometric pressure changes. Oxygen will first be consumed at the outer circumference of the fuel spill. As the fuel is degraded over time, the replenished oxygen supply will be available to support biodegradation closer and closer to the center of the spill. Almost any fuel contamination with a constant supply of oxygen will eventually biodegrade to carbon dioxide and water. Complete attenuation is more likely to occur in shallow and sandy soils, but less likely in asphalt or concrete covered areas, and in fine-grained or layered soils which will impede the supply of oxygen to subsurface microorganisms. Evidence of natural attenuation in soil, or the need for supplied oxygen (bioventing), should be established during the site screening process.

2.1.4.2 Natural Attenuation in Groundwater

The Air Force approach for documenting natural attenuation of dissolved contaminants is described in *the Technical Protocol for Implementing Intrinsic Remediation with Long-Term Monitoring for Natural Attenuation of Fuel Contamination Dissolved in Groundwater*. This document describes three lines of evidence that can be used to support remediation by natural attenuation:

- Documented loss of contaminants at the field scale,
- Contaminant and geochemical analytical data, and
- Direct microbiological plate counts or “microcosm” studies.

The first line of evidence involves using historical trends in contaminant concentrations to show that a plume is stable or receding and that a reduction in the total mass of contaminants is occurring at the site. This is by far the most persuasive argument for natural attenuation and one of the easiest to prove if quality historical data is available. If historical data for several wells indicate that concentrations are decreasing without any significant forward migration of the plume, the rate of natural biodegradation at the site must exceed or equal the rate at which BTEX and other dissolved contaminants are partitioning out of the source. In many states, natural attenuation alone is an accepted site remedy if historical data indicates plume stability and land use controls will prevent pathway completion. If historical data is incomplete, Appendix C provides additional information on the use of simple fate and transport models such as BIOSCREEN to predict the time required for plume stability.

The second line of evidence involves the use of geochemical data to show that decreases in contaminant concentrations are the result of biological destruction. When biodegradation is occurring, electron acceptor concentrations (oxygen, nitrate, sulfate, carbon dioxide, etc.) are depleted in the BTEX plume. Similarly, metabolic by-products (ferrous iron, methane, etc.) increase in areas of highest BTEX concentration and highest biological activity. This evidence can be used to show that electron

acceptor concentrations in groundwater are sufficient to support continued biodegradation of dissolved contaminants. The strong positive correlation between electron acceptor, electron donor, and by-product data proves that the historical disappearance of contaminants is due to biodegradation and not adsorption or dilution. Although a complete geochemical analysis will not be required for initial site screening, this data is inexpensive to collect and can be useful in convincing skeptics that contaminant loss is permanent. Methods of geochemical analysis are described more fully in Appendix C.

Although seldom required, laboratory "microcosm studies" or "bacteria plate counts" provide a third line of evidence that indigenous microbes are available and capable of degrading site contaminants. These studies are generally reserved for unique sites where the first two lines of evidence can not be demonstrated and for sites with non-petroleum or more toxic compounds that may be difficult to degrade.

2.1.5 Determining The Applicable Regulatory Framework

Before developing a remediation plan for any petroleum release site, it is important to first identify which environmental laws and regulations will apply to your particular site. Most petroleum contamination has originated from underground storage tanks or pipelines which should be regulated under state UST programs. Because most state UST regulations have been recently updated to incorporate risk management and RBCA strategies, this handbook provides specific guidance that will help you close sites under these regulations. Unfortunately, many petroleum contaminated sites were designated as RCRA sites in the early 1980's. Other sites were designated as CERCLA sites because other sites on the base were designated as national priority list (NPL) sites. Many sites are administered under the Air Force IRP which is a CERCLA-type process establishing the Air Force as the lead agency. If you are uncertain of the state or federal regulations which apply at your site, Appendix F has been developed to assist you in determining the proper classification. The AFCEE Toolbox also contains a summary of the latest state UST regulations. If you discover that a site has been incorrectly placed under RCRA or CERCLA authority, it may be worth your effort to

get the site reassigned under the appropriate state UST program. State UST programs generally allow for reduced documentation and significantly streamline the site closure process. Although the paperwork required to close RCRA and CERCLA sites is more cumbersome, the risk-based approach described in this handbook can be adapted to these regulations.

2.1.6 Selecting a Site Closure Approach

Two primary site closure approaches are discussed in this section: a risk management strategy based on land use controls and plume stability, and a strategy which relies on cleaning up a site to numerical risk-based goals. Although other approaches are available, they are generally variations of these two primary approaches.

The first risk management strategy uses a combination of demonstrated natural attenuation and land use control to ensure that no current or future exposure pathway is complete. These sites are placed in a long-term monitoring status or can be closed without long-term monitoring requirements if land use controls remain in place. This closure strategy is recommended for sites with well-defined limits of contamination and stable or receding plumes. This strategy is particularly useful on active installations where long-term land and groundwater use can be controlled. Section 2.2 provides additional details on this approach.

The second closure approach relies on more traditional risk assessment techniques to determine appropriate cleanup goals that are based on conservative exposure scenarios for the site (generally an industrial scenario). This approach focuses on specific contaminants of concern, such as benzene, and then uses a combination of monitored natural attenuation and source reduction to decrease contaminant concentrations to acceptable exposure concentrations which become the risk-based cleanup goal. Once the goal is achieved, industrial workers could theoretically be exposed to contaminated soil or groundwater without a significant health risk. This approach is embodied in the ASTM RBCA Standard E1739-95 that has been adapted by many state agencies. This

site closure method is appropriate for larger sites where future exposures cannot be prevented with simple land use controls, and for sites on closure bases where the regulating agency and the new landowner require remediation to more conservative risk-based standards. Section 2.3 provides additional details on this approach.

Figure 2.4 illustrates several key decision points for achieving risk-based site closures using these two approaches. Using available site data, determine which closure approach will likely be successful at your petroleum-contaminated site. Sections 2.2 and 2.3 provide a description of the key components of each approach.

2.2 MANAGING RISK THROUGH PATHWAY ELIMINATION

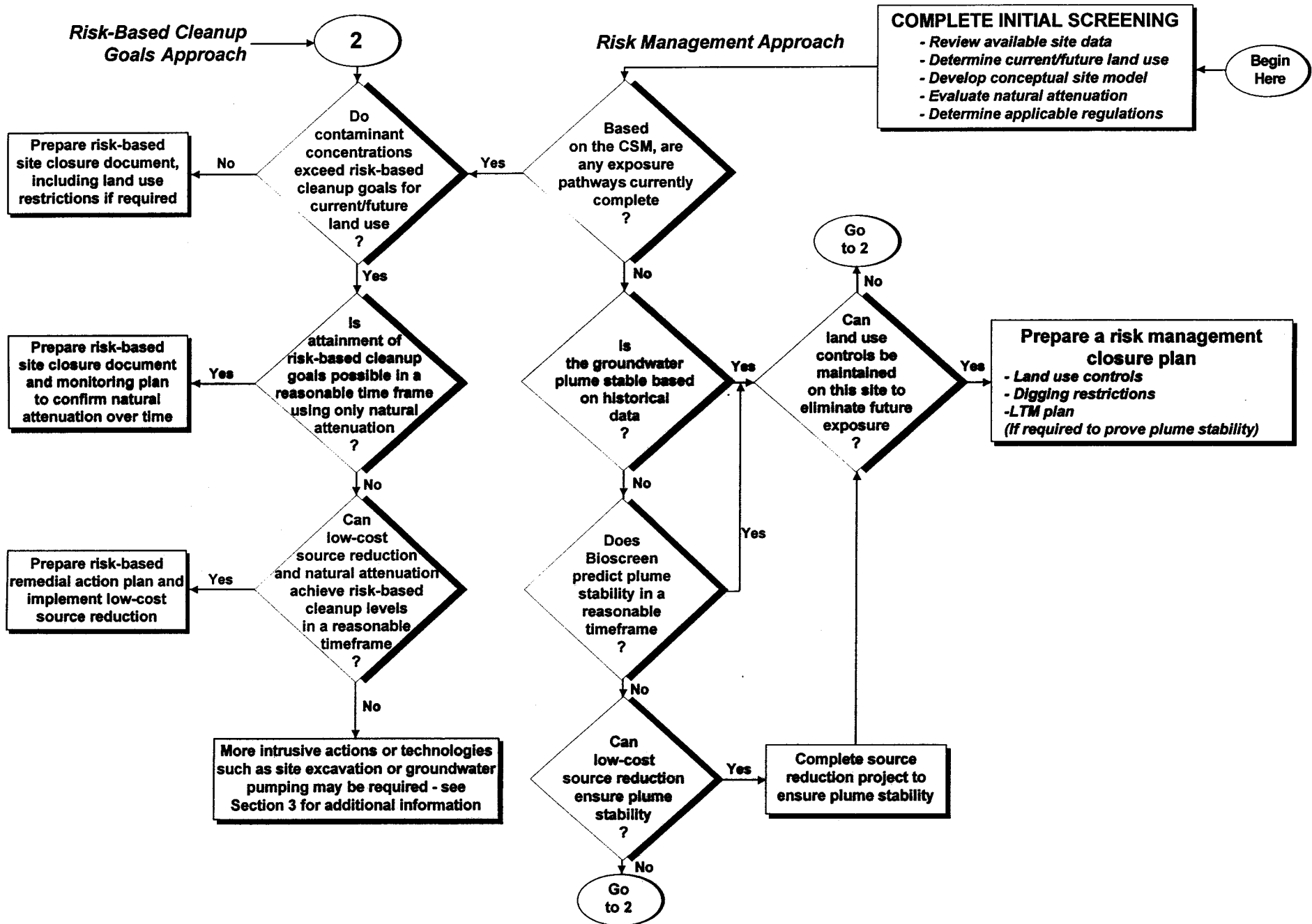
The underlying principle of this approach is that risk can be minimized through the use of land use controls if the contamination is stable and the long-term monitoring requirement is not excessive. Eliminating the pathway between the contamination and the receptor is one approach for eliminating risk. A combination of land/groundwater use control, source reduction, and natural attenuation can provide both a short-term and long-term pathway elimination with minimal impact on Air Force mission activities.

2.2.1 Completing a Pathway Analysis

A pathway analysis can begin once the full extent of soil and groundwater contamination has been defined and a CSM has been developed (review Section 2.1.3). Beginning with the soil, soil gas, and groundwater contamination, trace the potential pathways that could exist to site workers, nearby residents, and ecological receptors. For each potential pathway, use available site data to determine if exposure to the contaminant is occurring and under what circumstances future exposure could reasonably occur. Particular attention should be given to the soil gas pathway and any potential groundwater discharge to surface waters. Confined spaces such as utility vaults and buildings can accumulate fuel vapors. The air in these confined spaces should be analyzed for volatile organics, particularly benzene, to insure that this pathway is fully defined. The most common pathways to ecological receptors is through groundwater discharging to a nearby drainage ditch. Surface waters located

FIGURE 2.3

AIR FORCE RISK-BASED REMEDIATION APPROACH



2-15

downgradient of the site should be sampled to determine if the pathway is complete. Two or three surface water samples are generally required: a sample that is upstream of the potential discharge point, a sample in the middle of the discharge pathway, and a sample downstream of the discharge area.

2.2.2 Establishing Institutional Controls

Active Installations - Pathway elimination is very feasible on active installations because the base commander and base civil engineer have the authority to control future land use and the siting of future construction projects. The base civil engineer also maintains control of excavation activities through the "dig permit" and utility locator programs. This centralized control of land use and excavation activities can and should be used to eliminate potential exposure pathways at petroleum contaminated sites. For example, a restriction on excavation would prevent human contact with contaminated soil without proper safety precautions. A restriction on well drilling and deep excavation could prevent human contact with contaminated groundwater. In order for land use controls to be enforced, base planning personnel must have a current map delineating all soil and groundwater contamination on the base. All future construction and utility work should be formally checked against this map to see if the work would expose workers to contaminated soil or groundwater. Utility supervisors should also have a current map and be required to "check off" areas where emergency or scheduled repairs are required. If excavation must take place in contaminated soil, only properly protected workers should take part in excavation activities. If these written procedures are in place and followed at active installations, state and federal regulatory officials will be much more likely to approve a risk management approach to site closure.

Base Realignment and Closure (BRAC) Installations - The use of land/groundwater use controls on closure bases is complicated by the fact that the contaminated property is often being transferred to a private or public developer. Under these circumstances, long-term land use control can only be insured by recorded deed restrictions. Even with deed restrictions in place, local government must have

the authority to enforce these deed restrictions. Because of the greater uncertainty of long-term deed restrictions, state and federal regulatory officials will be less inclined to approve site closures which are solely dependent upon land use controls to prevent exposure to contaminants. However, based on AFCEE/ERT's risk-based site closure experience at eight BRAC sites, there is a growing acceptance of deed restrictions as a component of risk based site closures. The EPA "Brownfields" initiative has encouraged greater regulatory acceptance of land use controls at former industrial sites making them more attractive for redevelopment. The DoD BRAC Environmental Homepage (<http://www.dtic.mil/envirodod/envbrac.mil>) has additional information on the use of institutional controls on BRAC bases.

2.2.3 Evaluating Source Reduction

Many regulatory agencies will require some level of source remediation before agreeing to site closure. For example, an attempt at product recovery is often "mandatory" before site closure can be granted. Even under optimum site conditions, a 33 percent recovery of the free product is difficult to achieve (Freeze and McWhorter, 1997). It is AFCEE's position that most product recovery efforts will yield little reduction in groundwater contamination and that natural dissolution, smearing and product dispersion are more effective in reducing dissolved BTEX levels. A sample of free product should be collected and analyzed for BTEX mass fraction. At sites with highly weathered fuel, the BTEX remaining in the product may have little potential to impact long-term groundwater contamination. In the event that regulatory requirements for product removal prevail, several cost-effective alternatives for satisfying product recovery requirements are discussed in Section 3.

Other cost-effective methods of source reduction such as limited excavation, bioventing, and soil vapor extraction will be more effective at reducing BTEX residuals in soils and the capillary fringe. Potential benefits of source reduction include a rapid reduction in soil and soil gas risk, and a reduction in the leaching of BTEX compounds to groundwater shortening long-term monitoring requirements. Based on results from the AFCEE bioventing initiative, a 95 percent BTEX reduction can be expected at most

sites after one year of bioventing. Limited excavation, bioventing or SVE can also be used to satisfy regulatory source reduction stipulations. **(Note: If regulatory agencies require that soil be remediated to very conservative (residential) cleanup standards, it may be beneficial to pursue the risk-based cleanup goal approach described in Section 2.3)**

2.2.4 Using Natural Attenuation for Plume Containment

A second and equally important element of the risk management approach to site closure is providing evidence to the regulatory authorities that any groundwater plume emanating for this petroleum spill is stable or receding with no danger of migrating off-base or under another land use area (For example, a plume migrating from a BX service station toward a residential area). Several states such as Texas now require a series of 4 to 8 groundwater monitoring events to demonstrate plume stability. Site closure can now be granted in Texas if the plume is stable and land use controls are preventing completion of soil, soil gas, and groundwater pathways. Often plume stability can be proven by using historical sampling data and plume maps to demonstrate that concentrations are decreasing overtime and that the plume is not migrating. Appendix C provides additional details on how to scientifically document natural attenuation and predict plume migration.

The following subsections outline the minimum monitoring requirements for obtaining a risk management site closure. **(Note: If regulatory agencies require that groundwater be eventually remediated to residential drinking water standards, it may be beneficial to pursue a site closure using the risk-based cleanup goal approach described in Section 2.3)**

Long-Term Monitoring - Most regulatory agencies will require some level of groundwater monitoring to confirm that groundwater contaminants are decreasing in concentration and are not migrating from the site. The number of monitoring wells required will vary with site size and complexity. Figure 4.1 illustrates a simple long-term monitoring network. At least one upgradient well, one source area well and one

well at the leading edge of the plume are required at a small site where the groundwater direction is known. More wells will be needed if the plume direction is not well defined or exhibits seasonal shifts. Some states will require one or more "point-of-action" wells downgradient of the existing plume. Unexpected migration of contaminants to these wells can trigger the need for additional remediation. If this is the case, point-of-action wells should be located downgradient of the plume's leading edge. Section 4 includes additional details on setting up a long-term monitoring plan and locating monitoring wells.

Monitoring Frequency and Duration - If long term monitoring is required, both the frequency of sampling and the number of years of sampling should be negotiated in the risk management closure agreement. Annual monitoring is recommended for stable plumes and plumes with limited migration potential (low permeability/flat gradients). Monitoring should be conducted during the same month each year to minimize seasonal effects. Quarterly monitoring should be avoided unless significant seasonal changes are known to occur in the groundwater velocity or direction. Three years of annual monitoring should generally be sufficient to illustrate decreasing plume concentrations and plume stability. If regulatory agencies require more than three years of monitoring, or if historical plume concentrations are not decreasing, source remediation should be evaluated. The BIOSCREEN model can be used to estimate the benefits of source reduction on the long-term monitoring timeframe, or on achieving plume stability. Additional information on the BIOSCREEN model is provided in Appendix C.

2.3 REMEDIATION TO RISK- BASED CLEANUP GOALS

At many sites, regulatory agencies will require that the Air Force achieve some numerical cleanup goals before final site closure can be granted. As illustrated in Figure 2.3, there are several specific circumstances where risk-based cleanup goals may be needed to move the site closure process forward:

- Sites for which local regulations require cleanup to specific numerical criteria;

- Sites with completed exposure pathways which require more immediate reductions in soil or groundwater contamination, or;
- Sites where future land/groundwater use controls and excavation restrictions can not be guaranteed

In each of these situations, the establishment and application of risk-based cleanup goals to the site remediation process may result in a more reasonable closure agreement and limited long-term monitoring requirements. This section describes the key steps in selecting and establishing risk-based cleanup goals.

2.3.1 Fundamentals of Risk-Based Corrective Actions (RBCA)

The RBCA process involves a tiered approach in which assessment and resultant remediation activities can be tailored to site-specific conditions and risks (ASTM, 1994). Increasingly complex levels of data collection and risk evaluation may be performed to establish the type and magnitude of remediation required to reduce or eliminate unacceptable risks at a particular site. The tiered approach provides the flexibility to replace potentially overly conservative, generic exposure assumptions with site-specific information, while still providing the same level of human health and environmental resource protection. Three basic tiers of site evaluation (e.g., data analysis) have been established in the RBCA process:

- Tier 1 or screening-level evaluations;
- Tier 2 or site-specific evaluations; and
- Tier 3 or advanced site-specific evaluations.

2.3.1.1 Using Tier 1 Generic Screening Levels

Tier 1 risk-based screening levels (RBSLs) are conservative (health protective), generic cleanup criteria that define the amount of a contaminant that can remain onsite and not present an unacceptable risk to potential receptors. Many states have developed land-use-based RBSLs derived using reasonable maximum exposure (RME)

assumptions for industrial site workers. Industrial RBSLs represent the concentrations at which there should be no unacceptable threat to industrial site workers including excavation workers. Because industrial RBSLs are often based on 25 years of adult exposure to contaminated soil and groundwater, they are less stringent than residential RBSLs which assume child and adult exposure over a 30 year timeframe. For example, the State of South Carolina has established an industrial RBSL for direct contact with benzene in soil of 200 mg/kg significantly greater than the 22 mg/kg standard for residential land use.

Because industrial RBSLs represent worst case exposure scenarios, many states have streamlined the approval process for sites which have contaminant concentrations below these standards. Preparation of closure documents based on generic RBSLs are easy to prepare and do not require specialized risk assessment skills.

On many sites, maximum contaminant concentrations are less or very near to industrial RBSLs. Site closure agreements for these sites normally require some guarantee that land use will remain industrial and that soil or groundwater will be monitored until RBSLs are achieved through natural attenuation or engineered source reduction. On sites where contaminant concentrations significantly exceed RBSLs and the cost or timeframe to attain RBSLs is excessive, the development of site-specific cleanup goals may be beneficial.

2.3.1.2 Developing Tier 2 Site-Specific Cleanup Goals

Site-specific cleanup goals can be developed when generic RBSLs are unreasonably conservative and will result in a requirement for expensive engineered remediation or extended long-term monitoring. Site-specific cleanup goals will differ from RBSLs in several ways:

- These goals incorporate site-specific data rather than generic assumptions about land and groundwater use restrictions;

- They are based on more reasonable exposure routes given the likelihood that reliable and enforceable exposure controls will limit/prevent certain types of receptor exposures to contaminated media;
- They account for the positive impacts of natural chemical attenuation processes on interrupting potential exposure pathways and/or minimizing exposure-point concentrations; and
- They may sometimes be based on higher (less conservative 10^{-5} vs. 10^{-6}) target risk levels than RBSLs, once the decreased probability of actual exposure is documented.

Some states have specified the types of modifications, equations, and/or predictive models that can be used to develop site-specific cleanup goals (Kosteki, 1997). To ensure that these goals are acceptable, early consultation with regulatory authorities is recommended to establish the exposure scenarios that will be used at the site. On most Air Force fuel-contaminated sites the most likely exposure scenario involves short-term excavation with human contact with contaminated soil, soil gas, and groundwater. This limited exposure (90 days or less) will result in cleanup criteria that are often an order of magnitude higher than RBSLs. Appendix D provides additional guidance on the development of site-specific cleanup goals.

Before proceeding to Tier 2, Air Force environmental managers should evaluate the additional cost of developing and negotiating these site specific goals versus the cost of compliance with generic RBSLs. For example, if the site is small and RBSLs can be achieved by removing and treating contaminated soil, it may be more cost effective to actively remediate rather than fund the development of site specific cleanup goals. Sites where less than 100 cubic yards of soil are contaminated at levels above RBSLs can generally be remediated more cost-effectively using excavation and off-site treatment rather than pursuing site-specific cleanup goals. Professional risk assessors are generally required to develop site specific cleanup goals and many regulatory agencies are understaffed with qualified risk assessors to review and approve these cleanup

goals. Beware of assigning this work to consultants who are lacking experience in working with the risk assessment group within your local regulatory agency.

Approval of site specific cleanup goals will create significant savings on large sites such as fuel storage and transfer facilities with thousands of cubic yards of contaminated soil and large undefined groundwater plumes. The timeframe required to achieve site-specific cleanup goals will be significantly less and result in lower long-term monitoring costs.

2.3.2 Attaining Cleanup Goals Using Natural Attenuation

If existing contaminant concentrations exceed risk-based cleanup goals, the impact of natural chemical attenuation processes should be fully documented and factored into the evaluation. In addition to proving that the plume is stable, the rate of biodegradation must be estimated to determine an approximate timeframe for long-term monitoring. The case study on the KC-135 Crash Site (Appendix A) is an example of how natural attenuation was used to achieve RBSLs. Based on the BIOPLUME model, approximately 10 years of natural attenuation will be required to attain RBSLs at this site. Because the plume is stable or receding, and land use will remain industrial/flightline, the State of Michigan has agreed to a site closure agreement specifying long-term monitoring and land use controls.

Because the potential for exposure is greater if more contamination is left in place, more advanced models may be required to predict the effect of natural chemical attenuation processes on exposure pathway completion and exposure-point concentrations over time. Predictions about chemical fate over time and health-protective cleanup goals must be based on verifiable field evidence of natural chemical attenuation. The timeframe for achieving risk-based cleanup goals (levels of risk reduction) can be estimated and factored into long-term land use decisions. If the timeframe and cost of long-term monitoring is excessive, source reduction options should be considered. Appendix C provides additional details on how to determine the

effectiveness of natural attenuation at your site and Section 4 discusses how to set up an appropriate level of long-term monitoring and verification at your site.

2.3.3 Attaining Cleanup Goals Through Source Reduction

There are several situations when source reduction should be used to more rapidly or efficiently attain risk-based cleanup goals:

- There is an immediate risk to site workers due to explosive fuel vapors or vapors which are migrating into an occupied work space;
- There is a high probability that soil excavation will take place in soils which exceed risk-based cleanup goals;
- The groundwater plume is expanding and moving toward an important water resource (drinking water well or surface water), or;
- The timeframe for natural attenuation alone to decrease soil and groundwater contamination below risk-based cleanup goals is excessive.

In each of these situations, protection of human health should be the primary concern with cost the secondary concern. For example, at Charleston AFB Site ST-27, potentially explosive levels of fuel vapors were discovered beneath an occupied building. An interim remedial action was implemented using an internal combustion engine (ICE) to extract and destroy fuel vapors. With this immediate risk removed, a combination of bioventing and natural attenuation was selected to cost-effectively attain risk-based cleanup goals (see Case Study in Appendix A). At another installation, a gasoline spill contained high levels of benzene and was discharging directly into a drainage ditch at levels exceeding site specific cleanup goals. A natural attenuation study determined that biodegradation rates were slow and that nearly 100 years would be required for benzene concentrations to decrease to site-specific industrial cleanup goals. A combination of biosparging and bioventing was recommended to reduce the long-term source of contamination and prevent additional discharges of benzene into the

drainage ditch. Additional information on how to evaluate the need for source reduction and select an appropriate technology is provided in Section 3 and Appendix E.

2.4 MODIFIED SITE CLOSURE STRATEGIES

Several states such as California view all groundwater as a resource and have regulations which focus on resource protection (for drinking water) rather than allowing land use specific cleanup criteria. Recently, the more progressive regional water resource boards in California have recognized the value of natural processes as an in place treatment method for fuel contaminated aquifers. This shift in resource protection philosophy has been supported by the findings of the LLNL/UC plume study (review Section 1) which found that over 95 percent of the plumes in the State of California are stable or receding and undergoing in-place biological treatment. AFCEE recommends that a risk-management strategy using a combination of land use controls, proof of plume stability, and verification of contaminant destruction using long-term monitoring be pursued for small fuel-contaminated sites on active installations in California. For larger sites on closure bases, a combination of risk-based cleanup goals for soil contamination, proof of plume stability, and long-term monitoring may be appropriate for sites where industrial (no groundwater pumping) deed restrictions can be negotiated. On BRAC bases where deed restrictions are unacceptable, an engineered groundwater remediation system may need to be installed and successfully operating before a land transfer can be completed.

SECTION 3

EVALUATING SOURCE REDUCTION TECHNOLOGIES

This section will help the reader to determine when source reduction may be required at a site, provide guidance on effective technologies for the remediation of petroleum-contaminated sites, and assists environmental managers in the selection of an appropriate technology for a site-specific application.

3.1 DETERMINING THE NEED FOR SOURCE REDUCTION

The “source” of any fuel spill is generally defined as the area of highest fuel concentration. (The primary source is generally a leaking UST or pipeline, the secondary source is contaminated soil.) In some cases this will include free product and in most cases it will involve an area of highly contaminated soil from which contaminated soil gas or a dissolved plume migrates. Despite this concentration of contaminants, remediation of the source area is not always required or feasible.

3.1.1 The No Source Removal Option

There are several situations when source reduction may not be required or is not recommended. This can include sites where:

- No soil or soil gas pathway is complete and land use controls or worker protection (such as Level C and excavation restrictions) can be enforced to prevent human or ecological contact with contaminants;
- Soil contaminant levels are less than risk-based cleanup goals;
- No groundwater plume exists, or sites where the leaching of contaminants from soil to groundwater is not creating an expanding plume;

- The removal of the source is technically infeasible or prohibitively expensive.

The first two situations are likely at smaller sites which have existing land use controls or sites with little remaining source. The KC-135 Crash Site case study found in Appendix A illustrates the third situation. Although a source of contamination remains in the capillary fringe on this site, the resultant plume has been stabilized by natural attenuation processes and is in no danger of leaving an industrial/flightline area. The additional cost of source removal at this site produced no risk-reduction benefit nor did it significantly reduce the long-term monitoring timeframe.

There are also sites where the removal of the source is technically infeasible. Probably the most common situation is when free product has become submerged below the water table. This can occur at sites with shallow groundwater where the leaking tank or pipeline released fuel several feet below the water table or at sites in where reductions in regional groundwater use have resulted in rising water tables which have submerged free product and highly contaminated soils. In both of these situations, the cost of dewatering the source area and the uncertainty of success need to be weighed into the risk-based remediation decision. For example, it may be more cost effective to model the expected limit of plume migration and expand the long-term monitoring well network to accommodate plume expansion rather than try to limit expansion through source reduction.

3.1.2 The Engineered Source Reduction Option

Engineered remediation may be required to reduce or control identified risk or in response to other requirements such as regulatory direction, public pressure, or to achieve aesthetic goals. Often by using a combination of engineered remediation and natural attenuation, the chemical risks associated with the source area can be rapidly reduced, while natural attenuation and groundwater use controls can cost-effectively reduce the risk associated with the dissolved plume. There are several situations where engineered source reduction may be required or is recommended. This includes sites where:

- Emergency or interim actions are needed to eliminate an existing risk;
- Contaminant levels exceed risk-based cleanup goals for the intended land use;
- The resulting groundwater plume is expanding and could result in a future pathway completion;
- The rate of natural attenuation is slow and the plume will require monitoring for an excessive timeframe;
- Political or aesthetical considerations are dominating the decision making process.

Source reduction should be completed as soon as possible in situations where a pathway is complete and dangerous exposure concentrations (or explosive hazards) exist. For volatile fuel contamination, soil vapor extraction is often the most expedient method of removing risk. For sites with potential exposures exceeding risk-based cleanup criteria, source reduction and short-term land use or excavation controls will be required. Sites with potent source areas can produce dissolved levels of contamination that exceed the natural assimilative capacity of the aquifer resulting in continued plume expansion. Source reduction will decrease the loading of dissolved contaminants and allow the natural assimilative capacity to stabilize and eventually decrease the plume size and intensity. Based on AFCEE experience at over 50 natural attenuation demonstration sites, the most frequent justification for source reduction has been the cost savings associated with decreased monitoring requirements at a site.

At some sites there may be no current or anticipated future risk that would require engineered remediation. However, aesthetic considerations, public perception and political pressures may require that some form of engineered remediation take place. Despite the increasing awareness of natural attenuation, pathway elimination strategies, and risk-based cleanup goals, some regulators continue to demand the most aggressive cleanup approach for every site. A more reasonable approach is often accepted after contacting technical experts within the responsible regulatory agency and asking for their support. The removal of light non-aqueous phase liquid (LNAPL) is an example

of a cleanup requirement that may be driven by non-risk considerations. Given currently available technology, no more than 33 percent of the LNAPL mass can be recovered in most soils. Although a 33-percent recovery does not result in significant mass reduction or alter risk exposure concentrations, free product recovery will frequently be a regulatory requirement. At some sites it may be possible to demonstrate that the cost of product recovery is not justified by a commensurate reduction in risk. Nonetheless, under current regulations, free product recovery will be required at many sites independent of risk. It is important to understand what is driving the requirement for source reduction. This will determine site-specific remedial objectives and guide the process of technology selection.

3.2 IDENTIFYING THE REMEDIATION TARGET

It is important to identify where the greatest mass of contamination contributing to risk is located in the subsurface. For example, in a JP-4 jet fuel spill the benzene in groundwater may represent the chemical and receptor exposure pathway of greatest concern. Due to the relatively low solubility of benzene in water (relative to its solubility in JP-4) the mass of dissolved benzene typically is quite small. It is not uncommon to find that less than 1 percent of the mass of benzene at a site is dissolved in groundwater. In contrast, over 95 percent of the benzene mass is often retained in free product or fuel residuals trapped in soils near the source of the spill. *The most cost effective source reduction technology will be the one that can remove the greatest mass of contaminant risk at the lowest overall cost.*

Fuel contamination may be present in several forms:

Occluded - in soils, the LNAPL often exists at concentrations that are less than residual saturation. This fuel LNAPL is present as small oil droplets trapped between soil particles. This is the form that represents the majority of the contaminant mass at most sites.

Sorbed - this is contamination reversibly bound to the surface of soil particles and may represent a more significant mass at many sites than dissolved contaminant, but usually less than trapped oil droplets.

Continuous free phase - free product or recoverable (mobile) LNAPL. This is the free-phase product present in sufficiently high concentrations to form continuous streams and will flow into a monitoring well. This form normally represents less than 10 percent of the LNAPL mass present at most sites, and rarely exceeds 33 percent.

Soil gas - the fraction of contamination in this phase depends upon vapor pressure of the fuel and site-specific conditions. A highly volatile fuel, such as gasoline may generate 1 or 2 percent of the total hydrocarbon mass in the soil gas.

Dissolved - this fraction of the fuel generally represents less than 1 percent of the total mass.

While groundwater and soil gas are the media through which contaminants most readily migrate, the source of risk is generally concentrated in the soil or free product. It is also important to determine the position of the contaminant mass relative to the water table. Contamination can be in the vadose zone and/or the saturated zone depending on the depth at which the fuel release occurred. Generally, a major fraction of the LNAPL contaminant mass is above the seasonally low water table. At most sites the only mechanism for transport downward into the water table is the leaching of dissolved hydrocarbons. Leaching is minimized when soils are covered with concrete or asphalt and in low precipitation regions. Two exceptions occur when the regional water table has been lower in the past than it is now, and when fuel leaks from tanks that are installed below the seasonal low groundwater level.

The "smear zone" is defined as the layer between the permanent vadose and saturated zones. This is the zone within which the water table fluctuates seasonally,

where capillary forces maintain near-saturated conditions. The thickness of the smear zone is site-specific and is based on soil characteristics and seasonal water table fluctuations. At most sites the water table fluctuates only a few feet. The thickness of the capillary fringe also will depend on site-specific conditions. In a coarse sandy soil, the capillary fringe may be quite thin, a few inches at most; in a clay soil, the capillary fringe may extend several feet above the water table.

Before entering the technology selection process it is important to estimate the relative distribution of fuel contaminants among the various media and subsurface zones at the site. Appendix B provides guidance on soil and free product sampling procedures. Continuous soil coring and soil gas surveys completed during site characterization can provide a good estimate of where the greatest mass of fuel resides. Cohen and Mercer (1993) provide a detailed procedure for estimating total hydrocarbon mass in the soil and groundwater. It is often difficult to estimate the mass of continuous free-phase product which equates to the volume of recoverable product. This issue is addressed at greater length in the subsequent section on product recovery.

3.3 SOURCE REDUCTION TECHNOLOGY SELECTION PROCESS

Considerable guidance has been published on the process for identifying and screening remedial technologies under RCRA and CERCLA (USEPA, 1988, Environmental Services Directory, 1993). Detailed screening of technologies is seldom required for petroleum contaminated sites. This section will focus on a simplified process for selecting the most cost-effective technology for achieving specific risk-reduction or other remedial objectives. In many cases it will be more cost effective to abbreviate the technology evaluation process and simply apply a proven remedy. For example, if a small quantity of surface soils (<100 yd³) is contaminated with diesel fuel, it usually will be more cost effective to excavate and properly dispose of the soils (landfarm, landfill or off-site thermal treatment) rather than to go through a formal technology evaluation, selection, and implementation. Throughout the remediation planning process, the following question should be frequently asked: could the remedial objectives be achieved for less cost by going straight to a preferred remedy rather than

by continuing to study the problem? If the source area is large and the cost of active remediation is high, the selection process outlined in this section should be applied to achieve remedial objectives at the lowest cost. The general technology selection process is outlined graphically in Figure 3.1.

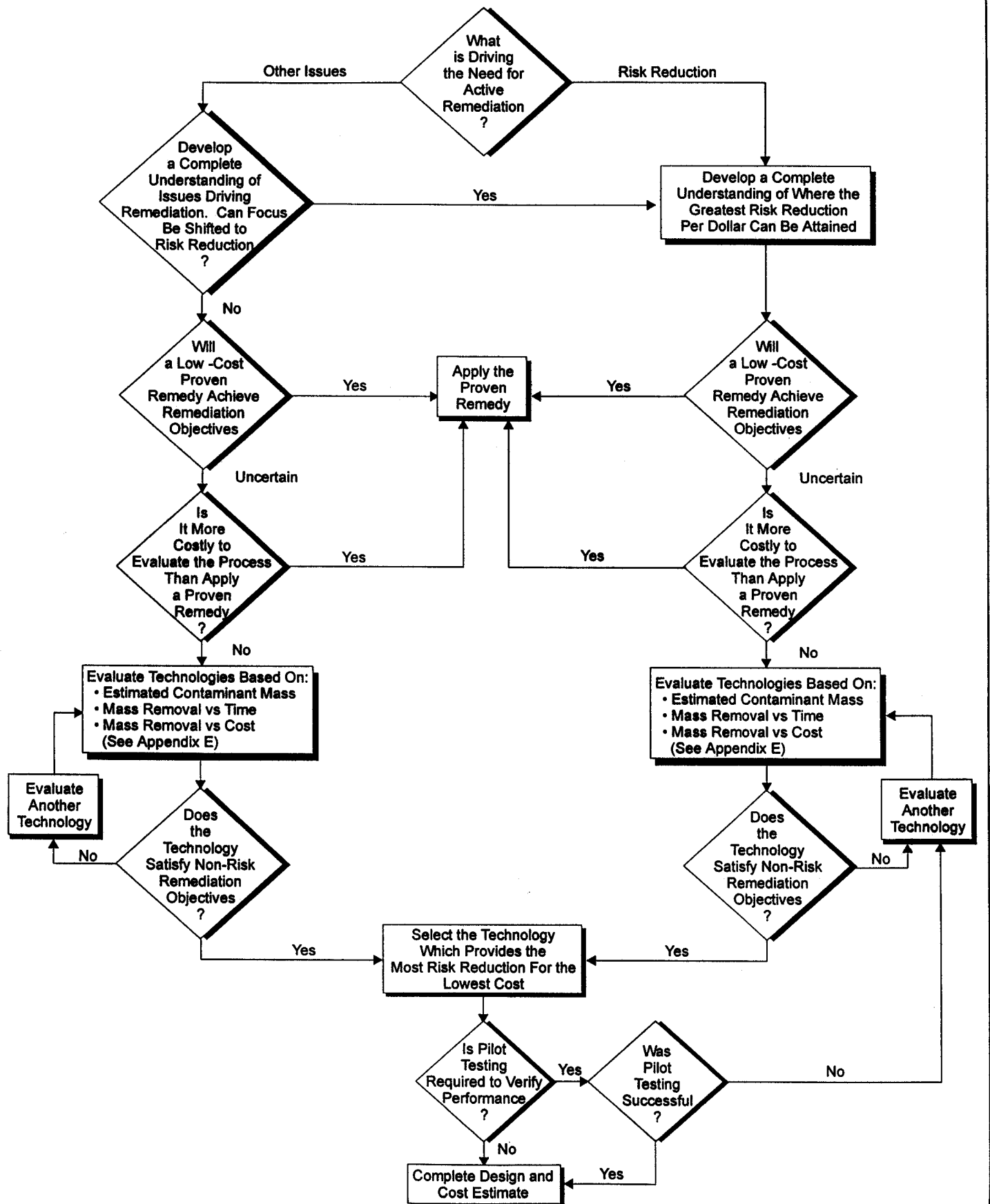
3.3.1 Technologies With Widespread Application

Many technologies are widely accepted and have proven to be cost-effective remedies for a variety of source reduction applications. Examples include soil vapor extraction (SVE) for treatment of volatile hydrocarbons (e.g., gasoline) in the vadose zone, bioventing for treatment of JP-4 or JP-8 in the vadose zone, and excavation and off-site treatment for small quantities of contaminated soils. The selection of a preferred remedy requires minimum evaluation of alternatives or pilot testing, and is usually accepted by regulators. If the estimated cost of applying a preferred remedy is lower than the cost of continuing to study a contamination problem, the preferred remedy should be applied.

Several factors must be considered when evaluating any preferred remedy, including the volume of contamination, the cleanup goals, and time constraints. For example, a small site with 400 yd³ of JP-4-contaminated soil could be remediated by excavation and offsite low- temperature thermal desorption for a cost of approximately \$75/yd³, or \$30,000 total cost. This would be a preferred remedy particularly if the site had a tight clay soil and was located on a closure base which was scheduled to be turned over to a private developer next year. Although the cost of bioventing on this site should be less than \$50/yd³, the time required to design and install a bioventing system, and the risk that bioventing would not reach the cleanup goal within 1 year, would out-weigh the potential cost savings. Conversely, if the site was not on a closure base, and had no time constraint on achieving closure status, it would be worth pursuing the bioventing option.

Table 3.1 provides a listing of technologies with widespread application for treating the environmental media contaminated by petroleum hydrocarbons. AFCEE has

**FIGURE 3.1
FLOW CHART FOR REMEDIATION TECHNOLOGY SELECTION**



**Table 3.1
Technologies for Remediation of Petroleum-Contaminated Sites**

Treatment Technology	Soils- Vadose	Soils- Smear	Soils- Saturated	Ground- water	Soil gas
In Situ					
Natural Attenuation	1	1	1	1	1
Bioventing	2	2	6	6	3
Soil Vapor Extraction	3	3	6	6	2
In Situ Heating Methods	3	3	6	6	4
Air Sparging/Bioventing	3	3	4	4,5	4
Biological Enhancements	4	4	4	4	6
In-Well Aeration/Recirculation	8	4	4	4	6
Barrier/Treatment Walls	8	8	6	4	8
Pump and Treat	8	8	7	4, 5	8
Free Product Recovery					
Skimming	8	4	6	6	8
Groundwater Depression	8	4	6	5	8
Bioslurping	4	4	6	5	3
Excavation and Ex Situ Treatment/Disposal					
Biopile	3	3	3	6	3
Low-Temperature Thermal Desorption	3	3	3	6	6
Offsite Disposal	3	3	3	6	6

1. Technology of first choice, usually lowest cost and effective; a preferred remedy.
2. Technology of choice if natural attenuation cannot be applied; usually a preferred remedy.
3. Technology that may be selected if 1 or 2 cannot be applied; may be a preferred remedy.
4. Technology that will provide some treatment, effectiveness uncertain; not a preferred remedy.
5. Technology that may be effective for containment; not a preferred remedy.
6. Technology may provide limited treatment, but is not designed for this purpose, and the effectiveness is uncertain; not a preferred remedy.
7. No immediate impact is expected, long-term improvement may occur as a result of application; not a preferred remedy.
8. No impact anticipated; not a preferred remedy.

recommended natural attenuation as the technical approach of choice for all environmental media. There is growing evidence that at most fuel-contaminated sites, natural attenuation alone will be sufficient to mitigate long-term risks to human health and the environment. When short-term risk is associated with soil contamination, bioventing should be considered a preferred remedy for vadose zone soils and the "smear zone". One exception is small sites with relatively small volumes (<100 yd³) of shallow soil contamination. At such sites, excavation and on-base biopile treatment, offsite thermal desorption, or offsite disposal will generally be more cost effective than *in situ* bioventing. Any time that less than 100 yd³ of soil is contaminated, the excavation and *ex situ* treatment/disposal remedy should be evaluated prior to spending additional time and money studying the problem.

The technologies presented here are routinely applied at fuel-contaminated sites. No effort was made to present the multitude of emerging technologies or those technologies that have produced questionable results. For example, bioaugmentation (the process of adding microorganisms to enhance biodegradation at a site) has been marketed for many years by numerous vendors, but peer-reviewed literature shows little advantage of bioaugmentation over biodegradation by native bacteria.

Numerous guidance documents, protocols, manuals, and other publications are available that provide extensive details on these technologies. Appendix F provides a listing of these available references. It is not the intent of this report to duplicate detailed information provided elsewhere. A brief summary of several technologies is presented in this section to assist in the process of technology screening and planning the remedial process. The actual design and implementation of engineered remedial options will require more detailed guidance.

Bioventing

Bioventing is the process of injecting or extracting air from the vadose zone to supply oxygen for aerobic biodegradation of fuel residuals. Bioventing is related to

SVE; the significant difference is in the design objectives. SVE is designed to maximize volatilization of contaminants, and bioventing is designed to maximize biodegradation of these chemicals. Bioventing systems usually employ a much lower air flow rate than SVE systems. Bioventing systems with air flow rates in the range of 0 to 20 cubic feet per minute (cfm) are not uncommon. Bioventing usually does not result in a air emissions requiring permitting or treatment.

According to the Air Force Bioventing Principles and Practice Manual, bioventing has been shown to successfully remediate petroleum hydrocarbons in the vadose zone at more than 95% of Air Force test sites. Bioventing has been less successful in desert environments where moisture may be limiting. Bioventing will not work if soil air permeability is too low to allow gas flow. This is rare, and in practice bioventing is usually successful even in low permeability soils. Bioventing can also be used to effectively treat the smear zone, which is particularly important if the fuel mass is concentrated in this zone. To the extent that the water table fluctuates, the deeper portion of the smear zone will be aerated during the seasonal low water table. Bioventing will also aerate the vadose zone immediately above the smear zone, allowing some limited treatment by diffusion. Air injection bioventing may depress the water table somewhat, resulting in additional smear zone treatment. Bioventing probably has minimum effect on groundwater contaminants. Any reports of bioventing contributing to decreased groundwater contaminant concentrations, are probably attributable to source removal rather than to oxygen transfer into the saturated zone.

Two limiting factors must be evaluated when considering bioventing as a source removal technology at a site: safety and time. At some sites air injection may not be safe, as is the case when the contaminant is volatile and there is a risk of displacing contaminated vapors into structures. For example, a gasoline spill adjacent to buildings with basements or close to vaulted utilities is a poor candidate for air injection bioventing. Numerous controls are available to monitor and control VOC vapor migration, but this concern has precluded air injection at some sites. Initially,

operating the bioventing system in the air extraction mode often will clear VOC vapors and allow subsequent operation in the air injection mode.

The other limitation on bioventing is time to achieve target cleanup goals. Cleanup time is site-specific, but normally bioventing takes a few months to years. As mentioned previously, BTEX contamination is routinely reduced by over 95 percent during the first year of bioventing, but heavier hydrocarbons, including PAHs, can take several years. Because BTEX (specifically benzene) is frequently the primary risk-driver at fuel release sites, its preferential removal in the bioventing process is a significant advantage in the risk-based remediation approach. In contrast, SVE will usually remediate BTEX and light hydrocarbons more quickly than bioventing, but often requires expensive off-gas treatment.

Soil Vapor Extraction

SVE is the process of extracting soil gas from the vadose zone to enhance the volatilization of contaminants and remove the vapor-phase contaminants for atmospheric discharge or aboveground treatment. SVE is a proven and widely applied technology for treatment of volatile contaminants such as gasoline and chlorinated solvents in the vadose zone. SVE air flow rates tend to be higher than those for bioventing, often as much as 10 to 20 times greater. SVE results in a contaminated air stream that may require an air emissions permit and frequently requires off-gas treatment. For sites with low levels (<10,000 ppmv) of soil vapor, SVE without off-gas treatment may be allowed in some states. For sites with high levels (>10,000 ppmv) of soil vapor contamination, AFCEE recommends the use of the internal combustion engine (ICE) technology. ICE equipment is capable of both the extraction and destruction of hydrocarbon vapors and has proven to be very cost-effective at vapor concentrations above 10,000 ppmv (AFCEE, 1994).

SVE has been applied successfully at thousands of fuel- (and solvent-) contaminated sites. In contrast to bioventing, low-permeability soils can be a serious limitation for SVE due to the higher required air flow rates. The impact of SVE on contaminants in

the smear zone and saturated zone are similar to those discussed for bioventing, except that when air is extracted the applied vacuum may cause the water table near the extraction wells to rise, resulting in less effective treatment of the smear zone at some sites.

The primary reasons for not using SVE are cost and feasibility. If air injection can be safely performed, bioventing is almost always less expensive than SVE. SVE is not feasible for removing heavier hydrocarbons and for treatment of fuels in some tight soils.

Free Product Recovery

In planning free product recovery, remember that the fraction of recoverable hydrocarbon contamination at most sites is small (i.e., rarely more than 33 percent of the total NAPL and usually much less). For example, if the initial TPH concentration in the smear zone is 60,000 milligrams per kilogram (mg/kg), then after a very successful free product recovery program, the concentration could still be over 40,000 mg/kg. The benefits of attempting free product are often political or "aesthetic". Rarely do these attempts result in a measurable reduction in risk. In light of this reality, AFCEE recommends that the cost of satisfying political or aesthetic requirements be minimized by first conducting simple "baildown" tests and installing passive skimming systems whenever possible. Only after careful pilot testing should any product recovery technology requiring expensive aboveground treatment be recommended for full-scale installation. There are a number of technologies in use for free product recovery that can be grouped into three categories:

- **Passive skimming**, where only product, and minimal groundwater or soil gas is extracted and no gradient is induced;
- **Groundwater depression**, where both product and groundwater are pumped, a cone of depression is produced resulting in a gravity gradient driving product flow; and

- **Dual-phase recovery** (aka bioslurping), where product, groundwater, and soil gas are extracted, and a vacuum is induced to drive product flow.

Passive recovery impacts only the continuous free phase in the smear zone. Groundwater depression relies on gravity flow and requires a pump-and-treat system to create the gravity flow that recovers mobile LNAPL from the smear zone. Dual-phase recovery has a similar impact below the water table as groundwater depression, but also extracts soil gas from the vadose zone, resulting in some biodegradation (hence the term "bioslurping") and some volatilization. The dual-phase extraction system also may induce additional flow of LNAPL from the capillary fringe that neither skimming nor groundwater depression will effect. The drawback of groundwater depression and dual-phase systems is the high cost of treating extracted groundwater and soil vapor.

Determination of recoverable product at any given site is more of an art than a science. The past standard practice of estimating product thickness in wells and trying to extrapolate a recoverable product volume has resulted in large investments in free product recovery systems that have failed to recover even 1 percent of the estimated product. AFCEE now recommends a series of simple baildown tests, limited pump down tests, and vacuum enhanced recovery tests to determine the likelihood of successful free product removal. These improved methods for pilot testing free product recovery systems are described in the *AFCEE Test Plan and Technical Protocol for Bioslurping* (see Appendix F).

Excavation and Treatment or Disposal

Soils can be excavated and treated on site or treated and disposed of off site. Excavation is normally the preferred remedy for small volumes of easily accessible, contaminated soil. The feasibility of excavation is a function of depth, soil structure, and surface structures at the site. Offsite disposal is frequently an option, but depends on the availability of facilities willing to accept fuel-contaminated soil. In some localities it is possible to dispose of hydrocarbon-contaminated soil at no cost where a landfill is short of daily cover and needs the soil. In other parts of the country, fuel-

contaminated soils can be disposed of as nonhazardous waste in a landfill for \$10 to \$100/yd³. If the soil must be disposed of at a hazardous waste landfill, transport and disposal fees will be much higher. Other offsite options include regional treatment facilities that may treat the soil thermally or biologically. In some locations it may be possible to use a predominantly sandy soil as feed material in an asphalt plant.

Low-temperature thermal desorption heats soils (and the fuel contaminants) to a temperature below ignition and above the vapor pressure. This desorbs the contamination from the soil and into the vapor phase. The VOCs in the air stream are then incinerated at a high temperature. Low-temperature thermal desorbers are available in mobile or may operate at fixed facilities near some Air Force installations. Mobile units that have relatively high mobilization costs and are only cost effective for sites with larger quantities of soil (usually more than 1,000 yd³). Onsite treatment costs of \$30 to \$60/yd³ are common for this technology. At some bases the soils from several small sites have been treated during a single mobilization, making the process more cost effective.

Landfarming is the spreading and mixing of contaminated soils at an aboveground facility to stimulate biodegradation; frequently volatilization is also an important treatment mechanism. It is an effective technology for treating a variety of petroleum hydrocarbons, and is in widespread use. The cost of landfarming is reduced as the soil volume increases, but generally falls in the \$20 to \$50/yd³ range. Drawbacks to this technology include the relatively large land area requirements, and in some climates, the seasonal nature of operations due to precipitation or cold temperatures.

Biopiles are piles of soil into which oxygen is introduced through ventilation pipes. Moisture and nutrients may or may not be added, and temperature may or may not be controlled. Piles may be covered with plastic when leachate formation is a concern. Costs tend to be higher than for landfarming, but less land is required, the process can be better controlled, and year-round operation is possible. The Navy has constructed centralized biopiles at several bases to treat soils from multiple sites.

3.3.2 Technologies With Limited Application

A second group of technologies is not recommended for widespread use but may have limited application on Air Force petroleum-contaminated sites. Although air sparging, in-well aeration/recirculation, biological enhancement, and pump and treat systems have achieved remediation at some sites, their success is far from universal. Based on available literature, there is no evidence to suggest these technologies will consistently achieve cleanup objectives. The following technologies have limited applications and should be evaluated on a site-by-site basis.

- Air Sparging/Biosparging
- In Well Aeration/Recirculation
- Biological Enhancements for Groundwater (Oxygen Addition Compounds, Nutrients, "Designer Bugs")
- Barrier/Treatment Wall Technologies
- In Situ Heating Methods (Steam Injection, RF Heating, Six-Phase Heating, etc.)
- Pump and Treat Methods

Air Sparging/Biosparging

Air sparging is the process of injecting air under pressure into an aquifer. The objective is to force the air to move through contaminated aquifer material and groundwater in as many small channels as possible. Treatment may occur either through volatilization or through biodegradation stimulated by adding oxygen. A sparging system often is coupled with SVE to collect the VOCs that have volatilized into injected air. Although air sparging has been applied at numerous sites, the current understanding of air sparging performance and effectiveness is limited. One potential concern is the tendency for injected air to form channels in the aquifer. When one of these channels intercepts a monitoring well, the air then bubbles up through the well,

stripping contaminants and oxygenating the well water. As a result, the monitoring well quickly appears "clean", although much of the surrounding aquifer remains untreated. This false indication of rapid treatment led to early enthusiasm for air sparging, and its indiscriminate application.

More recently researchers have found that many of the early "successes" of air sparging were not in fact successful remediation (Bass *et al.*, 1995). The physics of air flow in an aquifer are more complex than first thought, and a real understanding of air sparging is only beginning to emerge. It is clear that air sparging can have some impact on contaminated soils below the water table, and on contaminated aquifers; however, it is also clear that at many sites air sparging has been ineffective. One potential advantage of air sparging at some sites is that the channeling of air through the smear zone can provide better oxygen distribution than conventional bioventing, and also can remediate the vadose zone. Special site conditions may lend themselves to successful use of sparging to address dissolved fuel compounds. Sandy aquifers with shallow groundwater contamination may provide for more uniform treatment than sites with mixed sand, silts and clays.

The primary reasons for not selecting air sparging are uncertainty and infeasibility. Uncertainty is due to a limited ability to predict sparging effectiveness from site to site given the current state of the art. Infeasibility is usually discovered through pilot testing. One common problem is formation of large, horizontal air channels that allow injected air to bypass contaminated groundwater. At other sites, all of the injected air moves up to the vadose zone in the immediate vicinity of the injection point, resulting in a very small radius of influence. In some aquifers (silt and clay soils) the permeability is too low to inject air.

In-Well Aeration and Recirculation

In-well aeration is the process of injecting air into a well with three intended purposes: the stripping of volatile organics from groundwater that enters the well, the addition of oxygen to groundwater, and the displacement and recirculation of

groundwater outside of the well. The first two processes (stripping of volatiles and addition of oxygen) are almost certain to occur at any site, however, the recirculation of groundwater outside of the well has not been consistently proven in sandy aquifers and most certainly will not occur in low permeability soils. The obvious shortfall of this technology is the limited influence that oxygen addition or volatiles stripping will have outside of the well. In summary, this technology has not demonstrated a consistent ability to uniformly treat sandy aquifers, and has no application in low permeability silt and clay soils.

Biological Enhancements

Biological enhancements include the addition of cultured bacteria, surfactants, nutrients, and enhanced electron acceptors (oxygen, nitrate, sulfate) to soil or groundwater. A complete discussion of all enhancements is beyond the scope of this document. The following paragraphs provide the "bottom line" AFCEE recommendations on biological enhancements.

Based on the documented ability of naturally occurring microorganisms to degrade petroleum contamination, the addition of specialized bacteria to enhance biodegradation processes is not recommended. During the past twenty years there have been hundreds of bacteria cultures, special enzyme mixes, etc. which have been marketed as providing significant enhancements to natural processes. These additives have been recommended for injection into the soil or groundwater or mixed with soil in aboveground treatment cells. AFCEE and other independent evaluators have carefully reviewed the claims of many of these vendors and concluded that with few exceptions, natural bacteria are capable of degrading petroleum hydrocarbons at the same (or faster) rate as the specialized bacteria. Bacteria addition is not recommended for the biodegradation of petroleum hydrocarbons.

The use of surfactants to increase the solubility of polyaromatic hydrocarbons (PAHs) and other low solubility contaminants should be considered for aboveground treatment of soils contaminated with heavy oils. The addition of surfactants in

landfarming applications can improve the bioavailability of some regulated hydrocarbons and speed the biodegradation process. Unfortunately, because surfactants are organic compounds, they often create a new food source for bacteria and compete with contaminants in the biodegradation process. AFCEE recommends that any remediation plan that is considering the use of surfactants first complete a pilot test which compares the biodegradation achieved in soils with and without surfactants added. Because of the time that may be required (several years) to attain clean up goals for PAH compounds, other options such as low-temperature desorption technologies should be considered in lieu of landfarming for heavy oils.

Nutrient additions such as nitrogen and phosphorous are generally not recommended for in situ bioremediation. Bioventing pilot studies conducted at 135 test sites on over 50 Air Force installations concluded that natural levels of nitrogen and phosphorous are generally sufficient to sustain continuous biodegradation rates. Pilot testing has also shown that the addition of nutrients to existing bioventing systems had little or no impact on biodegradation rates (Miller, 1990). Other factors such as bioavailability and oxygen supply are more likely to be limiting the rates of in situ biodegradation. The use of nutrients to enhance the biodegradation in landfarming operations has been documented. The low cost of adding nutrients to soils in aboveground treatment projects make this practice a standard procedure for most landfarming operations. Although not as well studied, the addition of nutrients to groundwater to enhance the biodegradation of dissolved hydrocarbons is not expected to significantly enhance biodegradation rates. Any in situ application of nutrients to soil or groundwater should be proceeded with a pilot test which compares natural biodegradation rates to "nutrient enhanced" rates.

Although not as well studied, the addition of nutrients to groundwater to enhance the biodegradation of dissolved hydrocarbons is not expected to significantly enhance biodegradation rates. Any *in situ* application of nutrients to soil or groundwater should be proceeded with a pilot test which compares natural biodegradation rates to "nutrient enhanced" rates. Maintaining proper moisture content is a very important

environmental factor in most soil bioremediation projects. Although optimal moisture will vary with soil type, a range of 5 to 15 percent by weight is adequate in most soils.

Perhaps the most commonly used biological enhancement is the addition of oxygen to the soil or groundwater. Bioventing is the simple addition of air (oxygen) to the soil. Although not as efficient, biosparging is the addition of air (oxygen) to the groundwater. Other sources of oxygen addition are available such as pure oxygen, hydrogen peroxide and most recently oxygen addition compounds such as magnesium peroxide. Each of these oxygen sources has the potential to provide a higher concentration of oxygen to the groundwater than air sparging which is limited by the air-oxygen solubility of 8-12 mg/L in most groundwaters. However, each of these alternate oxygen sources has disadvantages. Pure oxygen can present a safety hazard, hydrogen peroxide is very unstable in most aquifers, and magnesium peroxide is very expensive to apply over an extended timeframe (approximately \$100 per pound of oxygen delivered). A common problem of all oxygen addition methods is the poor distribution of oxygen as distance from the point of injection increases. In most cases, this results in an excess of oxygen at the point of injection and little or no oxygen between points of injection. In light of the cost and inefficiencies of oxygen addition, AFCEE recommends that oxygen addition to groundwater only be considered at sites where the natural rates of attenuation are too slow to prevent contaminated groundwater from migrating to a potential receptor.

Permeable Barriers/Treatment Walls

One method of improving the uniformity of groundwater treatment is to install a semi-permeable barrier which can either physically or biologically remove contaminants as groundwater passes through the in situ treatment wall. Volatile BTEX contamination can be physically removed from groundwater by creating an air sparging curtain of closely spaced sparge wells or by placing a horizontal sparge well in a gravel-filled trench that intercepts groundwater flow. Sparging curtains will also add oxygen to the passing groundwater and may create a biologically active treatment zone that can

remove low levels of BTEX from the passing groundwater. Slurry mixtures of magnesium peroxide have also been promoted for this purpose, but the long-term cost of reinjection of this chemical could make this cost prohibitive on large sites. In situ treatment walls may be effective for preventing a BTEX plume from discharging to a drainage ditch or migrating off base property. This technology should not be implemented at a site where the plume is stable or forward migration poses no threat to receptors.

In Situ Heating Methods

Several in situ heating methods have been developed for enhancing the removal of contaminants from the soil and capillary fringe. Resistive heating, radio-frequency heating, and steam injection are some of the most commonly promoted in situ heating techniques. All of these technologies have had limited field application and are generally used to enhance the removal of high molecular weight compounds which can not be removed by soil vapor extraction and are difficult to biodegrade. Since most Air Force petroleum products can be biodegraded using bioventing or extracted using SVE, the additional cost of heating the soil to enhance SVE is difficult to justify.

Pump and Treat

Until recently, pump and treat was one of the most frequently applied technologies for sites with significant groundwater contamination. Over the past five years, most remediation experts have concluded that pump and treat is primarily a containment technology that should be used only when the dissolved plume migration pathway must be interrupted to prevent direct receptor exposure to contaminated groundwater. This is particularly true for petroleum hydrocarbons, given that almost all petroleum related plumes eventually stabilize under the influence of natural attenuation. As previously mentioned, the majority of the pump and treat systems now operating at fuel spill sites may be counter-productive to natural attenuation processes, and should be reevaluated.

3.4 REMEDIATION TIME AND COST ESTIMATES

Appendix E provides a useful guide for estimating the timeframe and cost of several remediation technologies. Two screening criteria are presented: the estimated time and the estimated cost to achieve a required reduction in BTEX concentrations in the soil or groundwater. *The actual cleanup time and cost will be site-specific.* The purpose of Appendix E is to provide general guidance, not to replace professional judgment and a more rigorous comparison of the alternatives based on site-specific factors such as the initial concentration of BTEX and the relative difficulty of working at different sites or different regulatory environments. These cost estimates are based upon professional experience, and that same experience has made it clear that it is difficult to estimate time and cost without evaluating many factors. Site-specific cost and cleanup times should be professionally estimated before initiating a costly remediation program.

A series of cost charts are provided in Appendix E for general technology evaluations and project estimating for remedial technologies frequently used for petroleum contamination. These costs are all for BTEX contamination in moderately permeable soils, and assume good conditions for application of the technology. Lower-permeability soils will typically result in higher costs and slower cleanup times. Application to heavier hydrocarbons such as PAHs will usually result in longer time frames and higher costs. These are typical costs for DOD sites using standard technology installations, not high-priced research projects. The time and cost estimates assume the project is implemented to the minimum technical specifications to meet the risk-reduction objectives.

3.5 PILOT TESTING

Pilot testing can serve two valuable functions in the technology selection and design process. The first function is to confirm that a preferred remedy such as bioventing will perform as expected at a specific site. Although technologies such as bioventing have achieved a 95-percent success rate at fuel-contaminated sites, there have been exceptions (e.g., several desert sites and wet clay sites) where bioventing was

infeasible. If your site falls into one of these exception categories, a bioventing pilot test is strongly recommended. (Prior to initiating a bioventing pilot test obtain a copy of the *AFCEE Bioventing Protocol or Bioventing Principles and Practices Manual for Pilot Test Procedures*.)

A second function of a pilot test is to collect key performance data so that a full-scale system can be properly designed and installed. This is most important at larger sites where multiple wells or monitoring points must be properly spaced, and blower units must be properly sized. As with other steps in the process, the cost of the pilot test must be compared to the cost and additional unknowns of proceeding without site-specific test results. For example, at a small hydrocarbon site it may be more cost effective to simply install a one- or two-well bioventing system than to conduct a pilot test and then return to add an additional vent well. The cost of pilot testing can be significantly reduced if the testing can take place at the same time the risk-based site investigation is underway.

There are several simple tests that can be performed during the site investigation and used to establish the feasibility of commonly applied technologies. Whenever a boring or probe is advanced, the field geologist/engineer should consider how that location could be used to collect pilot test information, natural attenuation data, or to prepare the site for a full-scale source reduction technology. Soil borings completed in contaminated soil should be completed as bioventing/SVE venting wells or soil vapor monitoring points. Soil borings completed in clean soil should be completed as background soil vapor monitoring points. Penetrations below the water table should be completed as either permanent or temporary monitoring wells for collecting contaminant or geochemical data. At least one well should be completed in the source area where free product is expected. This well can be used for product baildown testing.

Appendix E provides a summary of the most important pilot test objectives for several of the technologies listed in Table 3.1. The specific pilot testing procedures for these technologies can be found in the referenced protocols and technical literature.

SECTION 4

PLUME REMEDIATION

This section will describe several options for both managing and reducing the risks associated with contaminated groundwater plumes that have originated from petroleum spills. Due to the increased acceptance of natural attenuation as an in place remedy for fuel related contamination, many new options for site remediation and closure are available today that were not possible five years ago. This section will provide the reader with an overview of these options and the important steps that must be taken to secure a closure agreement on sites with dissolved groundwater plumes.

4.1 REVIEW OF REGULATORY OPTIONS

Section 2 described two strategies for managing and reducing risks at fuel contaminated sites. The approach used for petroleum-contaminated plumes on your installation will depend upon the regulations which apply to your site. Base environmental managers should be familiar with their state UST regulations and keep informed of pending legislation. In this rapidly changing regulatory environment, understanding the latest policy changes could result in significant cost and time savings. New RCRA and CERCLA guidance is available on the use of natural attenuation as a site remedy. As this guidance is implemented it should provide new site closure options for RCRA and CERCLA sites.

The first approach is based on the premise that if long-term land use and groundwater use can be controlled to eliminate exposure pathways, that natural attenuation processes will eventually reduce contaminant concentrations to levels that no longer require institutional controls. On these sites, the contaminated plume is

contained within an area where human or ecological contact with groundwater can be prevented. The concept of natural plume containment and gradual destruction is now accepted in many states and has become a recognized regulatory option. This option may not require long-term monitoring if plume stability and decreasing concentrations have been verified by past historical data.

A second option that has been adopted by many states focuses on the attainment of risk-based cleanup goals. These goals can be generic for the intended land use (residential, commercial/industrial) or based on less conservative, site-specific exposure scenarios. This option also makes maximum use of natural attenuation, but can include soil or source remediation to accelerated the attainment of cleanup goals. This option generally requires long-term monitoring to track the progress of natural attenuation toward the final cleanup goals.

It is important to point out that both the "plume containment" and "remediation to cleanup goal" approaches should rely on natural attenuation as the first choice of remediation. The primary difference between these approaches is the means by which risk is eliminated. Plume containment seeks to minimize risk by documenting natural attenuation and guaranteeing land and groundwater use control. Remediation to a clean up goal seeks to minimize risk by documenting natural attenuation and setting risk-based cleanup goals that establish a timeframe for removing land and groundwater use controls.

4.2 PLUME CONTAINMENT

4.2.1 Potential Applications

There are several situations where the plume containment strategy may result in the most cost-effective site remediation and closure process. In general, this strategy will be most useful on active installations where long-term institutional controls are under Air Force jurisdiction. This strategy also lends itself to spill sites with historical data that indicates that the groundwater plume is stable or decreasing in concentrations.

This combination of long-term Air Force control and plume stability provide an appropriate setting for implementing a plume containment strategy. Other situations that may lend themselves to this approach include:

Inaccessible Source Sites - Source areas can become inaccessible due to leaks occurring below the historic low water level or due to rising regional water tables which create a submerged layer of free product. Both of these situations create a continuous, long-term source of BTEX compounds. The options for removing submerged free product are limited, expensive, and largely ineffective. Source areas beneath large buildings and active aircraft aprons are also difficult to remediate due to the high cost and risk of installing horizontal extraction and bioventing wells.

Sites With Continuing Small Leaks - Despite significant Air Force progress in the area of spill prevention and detection, small fuel leaks (and human errors) will continue to occur in large fueling facilities. Because all soil and groundwater environments have the capability to biodegrade a certain mass of petroleum products each day, plume containment strategies may represent the most realistic approach for managing the risk at large active fueling facilities. Several states, have recognized the value of natural "mixing zones" to biologically degrade hydrocarbons and contain areas of contaminated groundwater. Regular monitoring of the "mixing zone" is required to ensure that fuel leaks do not overwhelm the natural biodegradation capacity of the aquifer. (Note: This approach does not relieve the base from the responsibility of mandated leak testing programs)

4.2.2 Demonstrating Plume Stability or Limited Migration

The plume containment strategy can only be implemented at sites where historical data indicate that the plume is relatively stable or very limited in its downgradient migration.

Plume stability can be demonstrated when the following five criteria are satisfied:

1. The direction and approximate velocity of groundwater flow is known.
2. The plume is defined by a minimum of four wells (see Figure 4.1)
3. Historical contaminant data (generally at least three years) indicates little or no forward migration of the plume.
4. The concentrations of contaminants throughout the plume, including the source area, are relatively stable or decreasing.
5. There is no downgradient pumping activity planned which will accelerate the plume velocity.

Table 4.1 illustrates a set of historical data for the KC-135 Crash Site at Wurtsmith AFB, MI. This plume is considered stable because the last three annual sampling events have shown that BTEX concentrations in the center and at the leading edge of the plume have remained stable or decreased. Some variations in the source area concentrations of BTEX are to be expected and do not indicate an unstable plume. Other data such as geochemical data (dissolved oxygen, nitrate, sulfate, ferrous iron, methane, etc.) are useful for demonstrating that plume stability is the result of active biological destruction within the plume, however, this data is not always required to demonstrate plume stability. A professional hydrogeologist may be required if you are uncertain of plume stability or if the timeframe for plume management becomes an issue. Simple analytical flow models such as BIOSCREEN are recommended if regulatory agencies require an estimate of the timeframe required before institutional controls can be removed. Appendix C provides additional guidance on collecting geochemical evidence and fate and transport modeling.

**Table 4.1 Historical BTEX Concentrations
KC-135 Crash Site, Wurtsmith AFB, MI
($\mu\text{g/L}$)**

Well	1992	1994	1995
Source Area	15,000	5,124	3,410
Plume	1,900	122	58
Plume	1,500	1,364	388
Leading Edge	28	<2	<2
Sentry Well	<2	<2	<2

4.2.3 Institutional Controls for Groundwater

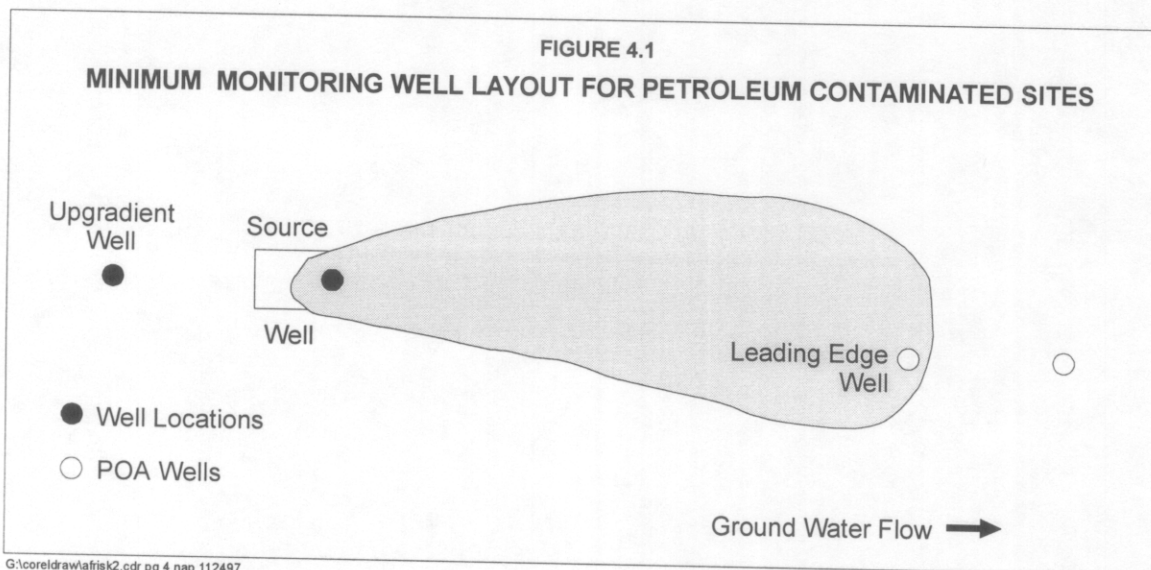
An equally important element of the plume containment strategy are the institutional controls that must be in place to ensure that humans do not contact contaminated groundwater. Two types of institutional controls are commonly used to prevent contact with groundwater. Excavation restrictions can be enforced on active Air Force installations through the dig permit program. Each base should maintain a current map of soil and groundwater contaminated areas on the base. Digging in contaminated areas should only be allowed if personnel have the proper protective clothing to prevent direct contact with soil and groundwater and have respiratory protection to prevent vapor inhalation. The second control is a restriction on the pumping of groundwater from the contaminated aquifer. This pumping restriction would not apply to deeper aquifers which are hydraulically isolated from shallow contaminated aquifers. This restriction can also be enforced through the digging permit program or through agencies issuing local drilling permits.

On BRAC installations, these excavation and drilling restrictions would need to be included in deed restrictions which are legally binding upon the new land owner. Because of the difficulty in enforcing long-term deed restrictions (particularly restrictions on excavations) the plume containment approach is not recommended for BRAC sites with shallow groundwater contamination (< 15 feet to groundwater). For sites where groundwater is not encountered in the first 15 feet, there is little chance of direct contact with groundwater and only well drilling restrictions would be required.

4.2.4 Establishing a Plume Containment Monitoring Strategy

4.2.4.1 Locating Point-of-Action Wells

A point-of-action (POA) well is any monitoring well which is located outside of the existing plume which is periodically monitored to ensure that contaminants are not migrating beyond the stable plume boundary. These wells should be screened over the same depth interval as the plume. At sites with a well-defined groundwater flow direction, two or three POA wells should be located downgradient of the plume. At sites with undefined or shifting groundwater flow directions, additional POA wells may be required to surround the plume. If historical data indicates that the plume is stable or receding, the well at the leading edge of the plume can be used as a POA well. A second well should be located downgradient at a distance which represents two to three years travel time for the groundwater based on the average groundwater velocity. Figure 4.1 illustrates the siting of two POA wells for a small plume with a well-defined flow direction.



Avoiding Point-of-Compliance Wells - Point-of-Compliance (POC) wells differ from POA wells in their regulatory intent. The migration of contaminants to a POC well at concentrations above some threshold has immediate regulatory significance and signals non-compliance. In contrast, the unexpected migration of contamination to a POA well signals the need for additional study or sampling at the site which may lead to a more aggressive remediation approach, the installation of another downgradient well, or more frequent monitoring. Because of this significant difference, the term "Point-of-Compliance" well should be reserved for those sites where the continued migration of the plume is likely and will result in off-base contamination or an imminent threat to a downgradient receptor such as surface water discharge of entering a production well used for drinking water. Hence the term POC well is not recommended for sites where the plume containment approach is implemented.

4.2.4.2 Monitoring Frequency

One of the primary objectives of any plume containment strategy should be to minimize the frequency of long-term monitoring. While some states may allow a site to be closed without long-term monitoring, most regulatory agencies and most base officials would like some assurance that the plume is shrinking and that it will eventually be reduced to levels that will no longer require institutional controls. Biannual monitoring is recommended for sites that have at least three years of historical data indicating a stable or shrinking plume. Annual monitoring is recommended for sites which lack historical data or for plumes that could still be migrating. Annual monitoring is also recommended for sites where small fuel leaks may still be occurring. It is important that monitoring events occur at the same month (30-day interval) each year to minimize seasonal differences. Some states may require that an annual monitoring report be submitted, or at a minimum, kept in an official site file.

4.3 REMEDIATING PLUMES TO CLEANUP GOALS

4.3.1 Potential Applications

Plume remediation to some cleanup goal is a more traditional approach for reducing and eventually eliminating the risks associated with petroleum-contaminated groundwater. Unfortunately, most of the early attempts to attain conservative residential cleanup goals have failed because of a general ignorance of the fate and

transport mechanisms that limit the rate at which any contaminant is released from the source into the groundwater. At many sites with significant gasoline or JP-4 contamination, the reduction of benzene to a residential cleanup goal of 1 to 5 ppb will require decades of engineered remediation. Only when more realistic risk-based cleanup goals are established can these sites achieve risk protection at a reasonable cost. Section 2.3 and Appendix D describe the process for establishing more realistic risk-based cleanup goals.

Several types of sites can be effectively remediated using risk-based cleanup goals. Some of the most common applications of this approach include:

- Sites where contaminants have naturally attenuated to levels that are near generic industrial or residential standards. In most states, these sites can be easily closed using No Further Action documents.
- Sites where the source of contamination is limited or easily accessible. On these sites it is reasonable for bioventing or some other cost-effective technology to significantly reduce the source so that both soil and groundwater contamination can be quickly reduced to risk-based cleanup goals.
- Sites where future land use is more difficult to control such as prime construction sites on active or BRAC installations. On these sites it may be advantageous to rapidly achieve risk-based cleanup goals that will allow excavation or unrestricted land use. Regulatory officials are also more likely to grant site closures to sites that have attained a risk-based cleanup level that is appropriate for the intended land use.
- Even on small sites with stable plumes (plume containment candidates) the cost of long-term monitoring can be reduced, particularly if the expected endpoint is residential cleanup criteria. By establishing a generic industrial or site-specific

clean up goal, the time to achieve that goal will generally be much less than the time to achieve residential criteria.

4.3.2 Using Natural Attenuation to Achieve Risk-Based Cleanup Goals

Once a set of realistic risk-based cleanup goals has been established for the site (review Section 2.3 and Appendix D), the timeframe required for natural attenuation alone to achieve these goals should be estimated. In some cases historical monitoring data can be used to estimate an overall rate of contaminant reduction and the time required to reach a risk-based cleanup goal. However, a model will be required to separate the potential effects of dilution and adsorption from biodegradation. Simple analytical models such as BIOSCREEN or more complex numerical models such as BIOPLUME can be used to estimate the rate of contaminant mass biodegradation in the plume. Appendix C provides a summary of these models and describes the input data that is required to use them. The *Technical Protocol for Implementing Intrinsic Remediation with Long-term Monitoring for Natural Attenuation of Fuel Contamination Dissolved in Groundwater* provides more in-depth guidance for the professional engineer or hydrogeologist. Once the timeframe to achieve remediation is known, two questions should be asked:

- Is the timeframe reasonable given future land use requirements?
- What is the long-term monitoring cost to achieve cleanup using only natural attenuation?

If the timeframe is not consistent with future land use (future construction site, future residential area), or if the cost to monitor the site to risk-based clean up goals is too high, the site manager should next determine if engineered source reduction could significantly cut the time or cost to achieve cleanup goals.

4.3.3 Combining Natural Attenuation and Engineered Remediation

Section 3 described several circumstances where engineered remediation may be required on a petroleum-contaminated site. In addition to reducing the potential risk posed by contaminated soils and soil vapor, engineered remediation can be used to reduce the mass of contaminants entering the groundwater. This reduction in leaching potential can accelerate the natural attenuation process and reduce the time and cost of long-term monitoring and site management. An example of this would be the installation of a bioventing system to reduce the source of BTEX entering the groundwater. This strategy was used at the former Carswell AFB fuel storage facility to reduce monitoring requirements by at least four years (see Appendix A Case Study).

Several technologies are particularly effective for enhancing natural attenuation processes. Bioventing enhances the natural attenuation of fuel residuals in the soil by supplying oxygen to soil microbes to stimulate aerobic biodegradation. SVE is very effective at reducing BTEX concentrations in permeable soils. Bioslurping combines free product recovery, SVE and bioventing and is particularly effective at reducing fuel residuals in the capillary fringe. All of these technologies will reduce the mass of BTEX and other contaminants dissolving into the groundwater. By decreasing the rate of dissolution, the natural assimilative capacity of the aquifer will more rapidly biodegrade contaminants to risk-based cleanup levels. The positive impact of BTEX reduction can be quantified by adjusting the leaching term in the BIOSCREEN or BIOPLUME III models, and then comparing the predicted timeframe for attaining risk-based cleanup goals with the "natural attenuation only" alternative. Bioventing or SVE has generally reduced the remediation timeframe by 30 to 40 percent and proportionately decreased monitoring and site management costs.

An alternate method of enhancing natural attenuation in groundwater is to artificially increase the supply of electron acceptors (generally oxygen). Although no engineered technology has reliably remediated saturated zone contamination, technologies such as

air sparging have shown some ability to volatilize BTEX and to increase dissolved oxygen in sandy aquifers. Other technologies such as oxygen releasing chemicals (hydrogen peroxide and magnesium peroxide) can increase dissolved oxygen in source areas, but are very expensive, particularly for large sites. Technologies which increase dissolved oxygen are most likely to be effective at sites with part-per-million levels of dissolved BTEX and sites where the natural rates of biodegradation are very slow (less than 0.1 percent per day).

4.4 ESTABLISHING A REMEDIATION MONITORING PLAN

The most important part of any site closure agreement is the remediation monitoring plan. Once the regulatory agency has agreed to the method of closure that will be used, they will want to know how you intend to verify that natural attenuation or engineered remediation processes are reducing contaminant concentrations. Regulatory agencies will also want some assurance that institutional controls will be enforced on the site. The remediation monitoring plan should clearly address these issues and should provide a framework for compliance with regulatory reporting requirements and for implementing contingency actions if remediation efforts fall short of goals.

4.4.1 Primary Components of a Groundwater Monitoring Plan

The remediation monitoring plan should clearly describe:

What data will be gathered? - This should be limited to contaminants of concern, groundwater elevations, and primary electron acceptors at the site.

Where data will be gathered? - Figure 4.1 illustrated a minimum four well monitoring network that would be appropriate for small sites with an established gradient. Additional wells will be required if the flow direction is known to change or if the plume is longer than 100 feet. POA wells may also be required in deeper portions of the aquifer to verify that vertical migration is not occurring.

How often will wells be sampled? - Annual sampling is recommended for sites with unstable or potentially expanding plumes. More frequent sampling should only occur if the groundwater velocity is high and downgradient receptors are at risk from undetected migration. Biannual or less frequent monitoring is recommended for stable plumes where fuel leaks are no longer a possibility.

How will the progress of site remediation be determined from this data? - For small, relatively stable plumes this could be as simple as keeping a table (see Table 4.1) or chart which illustrates the decreases in contaminant concentrations. For larger plumes that required initial modeling, plume migration and changes in concentrations can be checked against initial model predictions and the model recalibrated with new data. If data such as soil or soil gas samples have been collected as a part of soil remediation efforts, these results can also be factored into the leaching calculations that were used to estimate the timeframe required to achieve risk-based cleanup goals.

How will institutional controls be verified? - It is important that the site manager communicate with civil engineering and other organizations who have the authority to approve new construction and utility repair projects. An updated map of all fuel contaminated sites requiring excavation restrictions or drilling restrictions should be provided to these individuals. If excavation must take place in a contaminated area, workers must be protected from direct contact with contamination and from inhalation hazards. The site manager should make regular visits to all sites (even natural attenuation sites) to ensure that no exposure pathways are completed.

What actions will be taken if site remediation does not proceed as planned? - A significant increase in source area contaminant concentrations, migration of contaminants to a POA well, or new land use requirements are all events that signal a need to reevaluate the site remediation plan. Contingency actions should be commensurate with the risk of remediation failure. For example, there is little risk from an increase in contamination in a POA well if the site is in the middle of the base

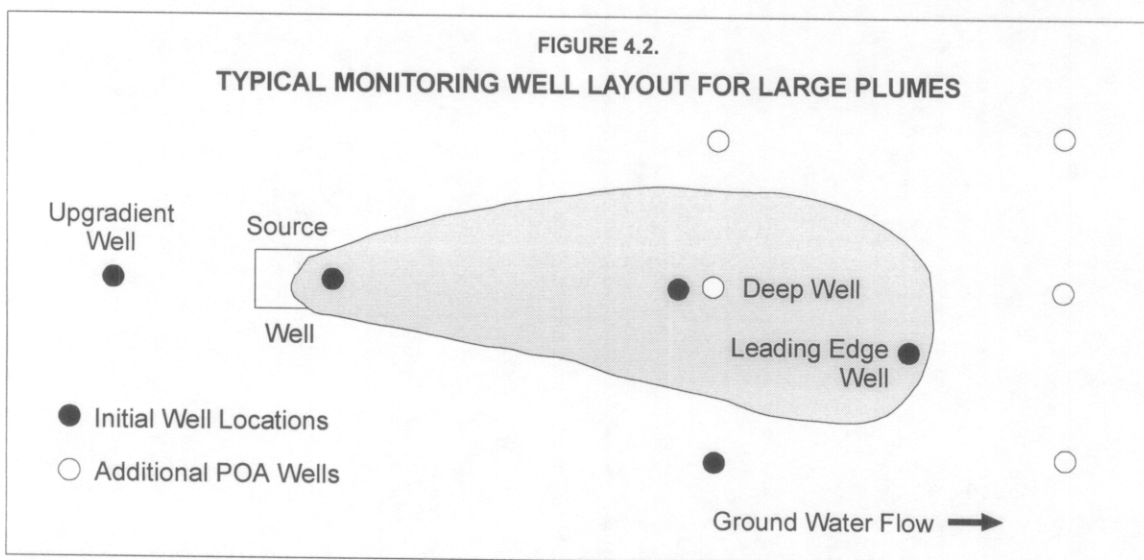
and is covered with concrete. The appropriate contingency action in this case could be as simple as increasing monitoring frequency to confirm a trend. In contrast, if a site is scheduled for transfer to a private developer in two years and source area concentrations increase by an order of magnitude, an immediate switch from natural attenuation to more aggressive bioventing/biosparging approach may be warranted.

4.4.2 Optimizing Long-Term Monitoring Plans

The purpose of this section is to assist site managers in evaluating and optimizing existing groundwater monitoring plans. There are three primary optimization opportunities on most sites.

- Reducing the number of monitoring wells to only those wells which are critical for plume evaluation.
- Reducing the frequency of sampling to match the anticipate rate of contaminant migration or change in concentration.
- Selecting only those analytes which are required to monitor remediation progress.

Due to inefficiencies in the site investigation process, most sites have more wells available than are needed to monitor remediation progress. Many of these wells are cross-gradient or too far downgradient to be useful in an optimized monitoring network. At a minimum, each plume should have one upgradient well to monitor for potential contaminant migration into the site, one source area well to monitor how the strength of the source is changing, one well at or near the leading edge of the plume and a POA well that is downgradient of the plume to monitor plume stability or migration. Figure 4.2 illustrates an example monitoring network for a larger plume and how this might vary from a smaller plume. Please refer to *The Technical Protocol for Implementing Intrinsic Remediation with Long-term Monitoring for Natural Attenuation of Fuel Contamination Dissolved in Groundwater* for recommendations on the location of more sensitive point-of-compliance wells.



The greatest potential savings in the long-term monitoring program can be gained by selecting the proper frequency for sampling. Far too many sites are subjected to quarterly monitoring requirements without any justification. The frequency of sampling should be matched to the estimated groundwater velocity, the rate of biodegradation, and most importantly the risk of plume migration. For example, a fuel-contaminated plume that is located in a low-permeability formation with a groundwater velocity of 5 ft/year will not require annual monitoring if the nearest POA well is 100 feet downgradient of the leading edge. In contrast, a highly contaminated plume that is located 100 feet from the base boundary may require semi-annual monitoring even if the groundwater velocity is 5 ft/year. Professional judgment is certainly required for each site, but as a rule, the AFCEE recommends annual monitoring as a baseline from which to deviate.

Once a list of contaminants of concern have been identified for remediation to risk-based cleanup criteria, future sampling and analysis should focus on this list of contaminants. For gasoline or jet fuel contamination, analysis by EPA Method 8260 or Method 8021B will generally be sufficient to detect all contaminants of concern. For diesel fuel spills, EPA Method 8270 may be required for semi-volatile contaminants of

concern. Site managers should resist additional types of analysis unless other contaminant groups are suspected and were not ruled out during the initial site investigation. In addition to contaminants of concern, sampling for primary biological electron acceptors such as oxygen, nitrate, sulfate and byproducts such as ferrous iron and methane can be completed. These analysis are considered optional for stable plumes but are recommended for plumes that are still migrating. Finally, groundwater elevations should be determined during each event to ensure that initial assumptions concerning flow direction and velocity can be verified.

SECTION 5

DOCUMENTATION

The purpose of this section is to provide RPMs with practical guidance on completing the documentation that will be required to present a risk-based closure to the regulatory community and the public in general. Suggestions for how to improve the quality of regulatory interactions are provided in this section, along with methods for educating the public on the subject of risk and risk-based remediation. A successful project begins with a well-developed work plan that outlines the entire remedial approach and sets forth the objectives of a risk-based closure. Once site data are collected and analyzed, and a risk-based remediation approach is formulated for a site, the findings must be organized and presented in a format that is acceptable to the regulators and that clearly communicates the risk evaluation process and recommended remediation approach. Annotated outlines for successful work plans and remedial action plans are provided in this section. The section also provides suggestions on how to develop and present an effective briefing to summarize a risk-based remedial decision.

5.1 GAINING REGULATORY ACCEPTANCE

Before a risk-based remediation project is initiated, it is essential that the proper regulatory framework has been established (see Appendix F) and the responsible regulatory officials have been informed of your intentions. State risk-based UST programs should govern cleanup and closure of fuel release sites whenever possible. Sites that are currently under RCRA or CERCLA jurisdiction should be reevaluated to see if they can be shifted to a more flexible state UST program. Regulatory acceptance will always depend upon the existing level of trust and respect that exists between the

base and the agency. In addition, the following actions are helpful in building regulatory acceptance:

- Base environmental managers and contractors who are well-versed in local risk-based regulations/guidance as well as the contents of this handbook.
- Informal discussions about the site and a potential risk-based closure.
- A project initiation briefing which includes several key regulatory officials. The Base environmental managers and the remediation contractor should work together to prepare a 30-minute informational briefing that provides an overview of the Air Force risk-based approach (tailored to local regulations), describes the site, and presents a preliminary CSM, plans for collecting natural attenuation and other data, and a schedule for the work plan and eventual corrective action plan.
- Following the briefing, informal regulatory input should be sought to help to focus of the work plan on issues of interest to the state or USEPA. A key issue is the regulatory agencies' position on the current and future land use designation (industrial vs. a potential residential scenario). Reaching an agreement that the site is and will remain an industrial area will often streamline the risk evaluation process.
- Regular communication throughout the project duration.

5.2 PREPARING A WORK PLAN

Several of the key technical aspects of work plan preparation are discussed in Appendix B.5. The purpose of this subsection is to provide an annotated outline of an example risk-based corrective action work plan. This is a comprehensive outline that can be abbreviated if significant site information already exists or if specific regulatory requirements dictate a different organization. At large or complex/controversial sites, the work plan may receive a complete regulatory review. At smaller (low-risk) sites, regulatory review of the work plan may not be necessary. Regardless of the level of

regulatory interest, the work plan must clearly communicate the intentions of the Air Force to collect additional data and the intended use of the data in the risk-based process.

ANNOTATED WORK PLAN OUTLINE FOR RISK-BASED REMEDIATION

Section 1 - Introduction

Sets forth the goals and objectives of the project and summarizes the scope of work and the organization of the work plan.

Section 2 - Review of Available Site Data

Describes the site background (operating and compliance history), site geology/hydrology, and the known source, nature, and extent of chemical contamination for each environmental media.

Section 3 - Preliminary Conceptual Site Model

Identifies contaminant sources, affected physical media, contaminant release mechanisms/migration pathways, receptor exposure points, and potential human and ecological receptors, based on available data. Identifies data gaps in the CSM. Describes how fate and transport models will be used to determine how risk will be reduced over time and distance from the source.

Section 4 - Proposed Sampling Activities

For each affected environmental medium, the data needs are identified and a sampling strategy is outlined. The sampling strategy includes a discussion of where samples will be collected, what they will be analyzed for, the data quality objectives and intended use of the data, and the scope of the quality assurance requirements. If there is a potential need for source remediation, this section also includes a discussion of pilot testing procedures.

Section 5 - Remedial Option Evaluation Process

This section provides a preview of how the site data will be used in the risk evaluation process and how plume stability, institutional controls, and risk-based cleanup criteria will be factored into the development of remedial alternatives for the site.

Section 6 - Proposed Project Schedule

Identifies key milestones, including draft and final deliverable completion dates, Air Force and regulatory review periods, and future presentations of results.

Section 7 - References

Appendix A: Site Sampling and Analysis Plan

Appendix B: Health and Safety Plan

Appendix C: Quality Assurance Project Plan (If the project is not covered under an umbrella QAPP.

5.3 REGULATORY PARTICIPATION IN RISK EVALUATION

As field data are validated and tabularized, an initial list of detected contaminants should be developed, and the CSM should be updated to eliminate receptor exposure pathways that are incomplete. A brief meeting with the regulatory official responsible for risk evaluations may be beneficial at this point. The revised CSM can be discussed with the goal of reaching an agreement as to which pathways and potential receptors should be evaluated. Initial results from the natural attenuation study including evidence of plume stability are also of interest. This level of informal interaction will lead to a successful and acceptable risk evaluation, which will form the basis for the risk-based management or remedial approach that can best accomplish those goals.

5.4 PREPARING A NO FURTHER ACTION CLOSURE DOCUMENT

A no further action closure document can be prepared for sites where contaminant levels are already below generic risk-based cleanup criteria or sites where no pathways exist to potential receptors and the state is willing to grant closure based on evidence of plume stability and adequate institutional controls. Many states have simplified the closure process by developing standardized forms that are completed by the site manager and submitted for regulatory review and approval. Other states require a brief report on site conditions and monitoring data which indicates either plume stability or compliance with risk-based cleanup goals. Regardless of the format, the content of these documents is generally spelled out in regulatory guidance. Key components of most no further action documents include:

- A brief site description including the nature of the petroleum spill
- A site map which clearly describes existing land use and surface features
- A map showing the location of soil and groundwater samples, monitoring wells and groundwater elevation contours
- A table or graph illustrating plume stability or comparing maximum contaminant values to risk-based cleanup criteria
- A discussion of institutional controls and how they will be maintained if contaminants still exceed risk-based cleanup goals.

5.5 PREPARING THE REMEDIAL ACTION PLAN

For sites which do not qualify for immediate closure, some form of remedial action plan will be required to describe the actions that will be taken to eventually achieve site closure. This subsection provides an annotated document outline that has been used to gain regulatory approval of risk-based site closure agreements at several AFCEE demonstration sites. The same general outline has been used to satisfy the requirements of for remedial action plans (RAPs), corrective action plans (CAPs) and engineering

evaluation/cost analysis (EE/CA) reports. Minor modifications will be required to satisfy USEPA or state-specific requirements, but the essential elements of most reports will be satisfied by this outline.

ANNOTATED OUTLINE OF A RISK-BASED CORRECTIVE ACTION SUMMARY DOCUMENT

Executive Summary

Provides a concise overview of the scope, objectives, methods, and major findings of the report.

Section 1 - Introduction

Includes a summary of the purpose and scope of the project, an overview of the risk-based approach to remediation as applied at the subject site, and a description of the report organization. The site background is reviewed, including the history of site operations and a summary of past investigations and remedial actions (if any).

Section 2- Site Characterization Activities

Describes the scope of data collection activities (number, types, and locations of samples) and a brief review of the sampling procedures used to investigate each environmental medium.

Section 3 - Physical Characteristics of the Site

Presents a complete summary of the regional and site geology, hydrogeology, and surface hydrology; current and future land and groundwater uses; and the general ecological environment near the site. Describes potential receptors and exposure points.

Section 4 - Contaminant Characterization

Uses tables and site maps to summarize the location and concentrations of detected contaminants in all environmental media including soil gas and soil gas flux test results.

Compares the contaminants in each medium to generic risk-based cleanup goals to create a list of potential contaminants of concern for each affected medium.

Section 5 - Quantitative Chemical Fate Assessment

Describes each of the fate and transport mechanisms that are operating to reduce the concentrations of contaminants. Simple, conservative models are first used to determine what pathways could potentially produce contaminant concentrations above generic screening levels and estimate the time frame for attaining these conservative cleanup criteria. In some cases, these models show that no receptor exposure pathways can reasonably be completed at the site. In these cases, an No Further Action decision can be supported. In many cases, current exposure concentrations exceed risk-based criteria but are expected to decrease due to natural attenuation alone. In this case, the document will proceed to Section 8. If contaminant concentrations greatly exceed generic screening levels and a Tier 2 risk evaluation is recommended, the document proceeds to Section 6.

Section 6 - Tier 2 Focused Risk Assessment (As Appropriate)

Presents the development and justification for less conservative risk-based cleanup levels based on site-specific receptor exposure scenarios (Guidance provided in Appendix D). The goal of this section is to provide the regulatory agency with a set of risk-based cleanup goals that are both conservative and realistic given current and future land uses at and downgradient from the site.

Section 7 - Pilot Testing of Source Reduction Technologies (Optional)

If pilot testing was completed during this or previous investigations, the results are presented in this section. Emphasis should be given to how effectively the technology has or should reduce concentrations based on the test results.

Section 8 - Comparative Analysis of Remedial Alternatives

This section describes several (two or three) remediation alternatives that can achieve risk-based cleanup goals. The alternatives are evaluated based on effectiveness, technical and administrative implementability, and present-worth cost following standard CERCLA feasibility study or RCRA corrective measures study guidance. Natural attenuation, long-term monitoring, and administrative land/groundwater use controls should always be developed as Alternative 1. Other alternatives can use source reduction technologies to enhance natural attenuation and to reduce the long-term monitoring timeframe. The low cost of natural attenuation is generally compared to the reduced time-to-compliance of alternatives using more active remediation methods.

Section 9 - Implementation of Recommended Remedial Action

Describes the full scope of the recommended remedial action, including a conceptual design of any full-scale source reduction technology, a long-term monitoring plan, and schedule for completing each aspect of the site closure.

Section 10 - References

Example of Appendices (will vary based on site complexity)

Appendix A - Analytical Results

Appendix B - Boring Logs, Well Construction Diagrams, Well Survey

Appendix C - Aquifer Test Data, Flow Calculations

Appendix D - Fate and Transport Model Calculations

Appendix E - Risk Assessment Calculations and Assumptions

Appendix F - Initial Screening of Remedial Technologies

Appendix G - Site Specific Sampling and Analysis Plan

5.5 EFFECTIVE PRESENTATIONS

Because risk-based corrective actions are completed in an iterative process, there is no substitute for good communications, including face to face meetings with regulators, at key decision points in the process. Based on recent experiences at 12 AFCEE risk-based remediation demonstration sites, several suggestions are offered to help improve the general effectiveness of presentations to the regulatory community and general public:

- Plan for a minimum of two face to face meetings, one to describe the risk-based approach for this specific site (a review of the work plan) and a second to describe the recommended remedial approach based on the risk evaluation. More complex sites may require progress meetings as described in Section 5.3.
- Know your audience; their technical strengths and weaknesses, and their sensitivities and priorities. If your regulatory contact is lacking in experience, a major portion of the presentation should focus on educating them on the Air Force remediation strategy. Presenting a simple case study of a completed risk-based closure can assist in this process.
- Use simple and professionally prepared graphics. There is no substitute for a good picture to illustrate a conceptual site model or to compare BTEX concentrations and dissolved oxygen utilization on a site map. For most audiences, a "picture is worth a 1000 words".
- Try to stay away from unfamiliar acronyms and terminology. This requires a concerted effort because the risk evaluation process is noted for having its own language and code words.
- Make sure that your presentation stresses that these are Air Force "recommendations" and that your actions are "proposed". Regulators need to get a clear message that they are included in the decision making process.

- Leave time at the end of the meeting for questions. Encourage the audience to write down their questions and try to resolve as many questions as possible at the meeting. Make sure you have someone in the room who was involved in the field work and risk evaluation as most questions seem to fall into these two categories.
- Always provide a set of meeting minutes to the participants within a week of the meeting, including a list of action items and who is responsible for resolution.

Finally, there is no substitute for preparation and practice. If a consultant will be making the presentation for the Air Force, it is important to arrange a pre-brief so the Air Force "team" understands the major conclusions and recommendations and is prepared to answer predictable questions.

APPENDIX A CASE STUDIES:

**Case Study A
Site OT-45
Wurtsmith AFB, Michigan**

**Case Study B
KC-135 Crash Site
Wurtsmith AFB, Michigan**

**Case Study C
Site ST-27
Charleston AFB, SC**

**Case Study D
Site ST-14
Carswell AFB/NAS Fort Worth JRB**

CASE STUDY A
SITE OT-45
WURTSMITH AFB, MICHIGAN

INTRODUCTION

Parsons Engineering Science, Inc. (Parsons ES) was retained by the United States Air Force Center for Environmental Excellence (AFCEE) to prepare a remedial action plan (RAP) in support of a risk-based remediation decision for soil and groundwater contaminated with fuel oil hydrocarbons at Air Force Installation Restoration Program (IRP) Site OT45 at Wurtsmith Air Force Base (AFB), Oscoda, Michigan (the Base). The purpose of the RAP was to develop and describe a recommended remedial action to be implemented at Site OT45 which met the requirements of the State of Michigan Department of Environmental Quality (MDEQ).

As described in the main text of this handbook, risk-based remediation is designed to combine natural physical, chemical, and biological processes with low-cost source reduction technologies such as *in situ* bioventing, as necessary, to economically reduce potential risks to human health and the environment posed by petroleum releases. The RAP was prepared as part of a multi-site initiative sponsored by AFCEE to develop this handbook on how best to implement risk-based corrective actions (RBCAs) at fuel-contaminated sites.

REGULATORY FRAMEWORK

The MDEQ has adopted a tiered, risk-based approach to the remediation of petroleum hydrocarbon contaminated sites that is similar to the American Society for Testing and Materials (ASTM) RBCA process and Air Force strategy. This approach allows for the establishment of site-specific corrective action requirements based on an analysis of potential receptor exposures to chemical contamination at or migrating from the release site. Both generic cleanup criteria (developed by the MDEQ) and site-specific chemical fate and exposure data can be used to identify the most cost-effective remedial strategy for a particular site.

The first level of evaluation in the MDEQ's approach is a Tier 1, or screening-level, assessment where contaminant concentrations measured in site media are compared to MDEQ-defined, nonsite-specific target concentration goals, which are based on land use and conservative exposure assumptions. These concentration goals are also known as risk-based screening levels (RBSLs). The MDEQ has defined three types of generic (i.e., non-site-specific) cleanup criteria based on current and foreseeable land use (MDEQ, 1995a and 1995b). Generic cleanup criteria have been defined for unrestricted (i.e., residential), industrial, and commercial land use assumptions. Generic cleanup criteria were developed by the MDEQ using standardized algorithms designed to be protective of human health under each of the three land use scenarios. As presented in Section 3 of the handbook, some states have developed their own screening criteria, making the development of Tier 1 RBSLs unnecessary. The State of Michigan is a good example of where the state regulatory agency has already defined Tier 1 RBSLs, making it easy and very simple to perform a Tier 1 evaluation.

The generic cleanup criteria or RBSLs are used to identify which, if any, contaminants and environmental medium, may warrant additional evaluation or remediation to protect human receptors. If measured site concentrations do not exceed the applicable generic cleanup criteria, no additional remedial action will be necessary.

other than maintaining the land use in accordance with the exposure assumptions used to derive the generic cleanup goals. However, in the event that measured site concentrations exceed the applicable generic cleanup criteria, additional corrective action or a more comprehensive evaluation (i.e., Tier 2) must be pursued.

A Tier 2 evaluation is more comprehensive than a Tier 1 analysis because it requires quantitative contaminant fate and transport calculations and possibly the development of site-specific remediation goals or site-specific target levels (SSTLs) based on site-specific exposure assumptions. The State of Michigan allows the development of SSTLs if warranted. Refer to Section 3.2 of the handbook for further discussion on the development of SSTLs. The quantitative Tier 2 chemical fate assessment can be used to identify if any unacceptable exposures could occur at the site over time and whether remediation to generic cleanup criteria is possible using different types of remedial approaches. Although Tier 2 evaluations usually involve more rigorous analysis and may require use of institutional controls or engineering barriers to ensure that exposure conditions do not change over time, they should result in a more focused remediation of those contaminants that actually pose a risk to potential receptors. A Tier 2 evaluation will result in the same level of health protection as a Tier 1, because remediation is focused on those elements that pose a risk given site conditions.

SITE BACKGROUND

Operational History

Site OT45 is located in the northern portion of the Base, and is the site of a former 1,000-gallon heating fuel oil underground storage tank (UST). The UST was located adjacent to Building 5608 in the Defense Reutilization and Marketing Office (DRMO) complex. After the heating oil UST failed a Tracer Tight™ tank test, it was purged in October 1991, and remained empty until it was removed in May 1992 (ICF, Inc., 1993). Wurtsmith AFB was placed on the 1991 Department of Defense Base Closure and Realignment Commission's list for closure, and was officially closed on June 30, 1993.

Previous Investigations

Two groundwater monitoring wells (W-OT45 and E-OT45) were installed at each end of the former UST location in 1992 when the UST was removed. Composite soil samples were taken during this effort, and analyzed for benzene, toluene, ethylbenzene, and total xylenes (BTEX) and polycyclic aromatic hydrocarbon (PAH) compounds. The only compound detected was 4-nitroaniline, which was measured near the reported detection limit (ICF, Inc., 1993 and 1994).

Site OT45 also was partially characterized during a 1992 remedial investigation (RI) and a 1993 draft feasibility study (FS) under the Air Force Installation Restoration Program (IRP) by ICF Technology, Inc. (ICF, Inc. 1993 and 1994). The FS concluded that, although the approximate extent of soil contamination was determined, the downgradient extent of the groundwater contaminant plume had not been adequately defined. The FS document was completed in 1994.

Ethylbenzene, toluene, total xylenes, fluorene, naphthalene, and phenanthrene were the only contaminants detected in soil samples collected as part of the 1992 RI. Site-related contaminants were only detected in soil samples collected from the interval immediately above the water table (smear zone) during the 1992 RI. Ethylbenzene, phenanthrene, naphthalene, and total xylenes were measured in soil samples collected from the smear zone at concentrations that exceeded generic industrial leaching criteria (based on data presented by ICF, Inc., 1993). These criteria were developed for industrial sites to prevent adverse impacts to groundwater due to contaminant leaching.

Groundwater samples were collected from the five existing monitoring wells during the RI. All collected samples were analyzed for BTEX, methyl tertiary butyl ether (MTBE), and PAHs. Fluorene, naphthalene, phenanthrene, and the BTEX compounds were the only contaminants detected in groundwater samples collected during the 1992 RI. Naphthalene and phenanthrene were the only compounds detected during the RI at concentrations that exceeded generic cleanup criteria developed to protect onsite industrial workers.

The FS concluded that natural attenuation of contaminants in impacted soils at Site OT45 would be considered protective of human health and the environment, but that measured concentrations of hazardous substances in the groundwater may present an unacceptable threat to offsite receptors unless an active remediation technology, such as groundwater extraction and treatment or biosparging, was implemented (ICF, Inc., 1993). However, the closest receptors are located more than 1 mile downgradient from Site OT45, and calculated risks to these receptors due to exposure to contaminated groundwater were based on onsite sampling data. The RI baseline risk assessment (BRA) for Site OT45 did not consider the effects of natural attenuation processes on groundwater contaminant mass over time and distance. The RI and the FS reports both stated that the likelihood that these offsite receptors would be exposed to hazardous substances at hazardous concentrations was very small to virtually negligible (ICF Inc., 1993 and 1994).

DEFINING SITE CHARACTERIZATION DATA REQUIREMENTS

In order to make a credible and defensible RBCA decision for this site, an adequate amount of suitable site characterization data must be collected. Sufficient data must be collected to conduct a quantitative fate and transport analysis, perform an exposure pathway analysis, and evaluate the potential treatability of contaminated media using low-cost remedial technologies and approaches. As part of the risk-based investigation at Site OT45, emphasis was placed on filling data gaps identified during previous remedial investigations and on collecting data relevant to documenting the *in situ* biodegradation of fuel hydrocarbons in soil and groundwater.

After a review of previously collected site data, data gaps and target analytes were identified. Data gaps were determined by reviewing a preliminary conceptual site model (CSM) (Section 4 of the handbook) to identify potential contaminant migration pathways that had not previously been adequately quantified. Target analytes were identified based on the chemical constituents of the known contaminant source, heating fuel oil, and the results of previous sampling activities at the site. It was determined that additional soil gas, soil gas flux, surface soil, subsurface soil, and groundwater samples were required to adequately quantify potential contaminant migration pathways

and associated risk at Site OT45. Source reduction technology pilot testing, present and future land use, and groundwater use data also were required to determine whether the engineered remediation recommended in the FS was warranted to provide the desired level of protection for receptors that could reasonably be exposed to site-related contamination.

Based on the chemical composition of heating fuel oil, the BTEX compounds and the PAHs naphthalene, fluorene, fluoranthene, and phenanthrene were identified as the target analytes for all media Site OT45. It also was determined that electron acceptor and other groundwater geochemical data would be required to facilitate an evaluation of the natural attenuation potential of dissolved hydrocarbon contamination.

SITE INVESTIGATION

An initial field investigation was conducted by Parsons ES at Site OT45 in September through October 1994. The following sampling and testing activities were performed by Parsons ES at Site OT45:

- Collection of soil gas samples at 3 locations;
- Collection of soil gas flux samples at 4 locations;
- Drilling and installation of 8 new permanent groundwater monitoring wells, 2 soil gas (vapor) monitoring points, 1 air injection bioventing test well, and 1 biosparging point;
- Collection of 3 surface soil and 14 discrete subsurface soil samples from 12 new soil boreholes for field screening and fixed-base analytical evaluation;
- Collection of 14 groundwater samples for field and/or fixed-base analytical evaluation;
- Aquifer slug testing at 5 groundwater monitoring wells;
- Completion of an air permeability test and an oxygen influence test to assess the effectiveness of bioventing at stimulating natural biodegradation of heating oil hydrocarbons in unsaturated soil; and
- Completion of initial testing at the biosparging point to define optimum operational parameters in the event that a full-scale biosparging system is required to promote rapid natural biodegradation of heating oil hydrocarbons in the saturated soils and the shallow groundwater.

Figures A.1 and A.2 show all of the sampling locations at Site OT45. Table A.1 lists the analytical method used for analysis of each media at Site OT45.

In addition to pilot test and analytical data, current and future land use information was collected during the site investigation at Site OT45 to allow determination of what generic, land-use based, screening criteria would be appropriate as a Tier 1 evaluation tool for the site. Site OT45 has effectively been an unused

property since the heating oil UST was removed in May 1992. However, due to the site's proximity to other facilities in the northern part of the Base, the current land use at Site OT45 could be conservatively classified as industrial.

Wurtsmith AFB was placed on the 1991 Department of Defense Base Closure and Realignment Commission's list for closure. Wurtsmith AFB was officially closed on June 30, 1993. The Air Force plans to dispose of excess and surplus real property and facilities as soon as environmental restoration is achieved, and pursuant to specific federal property disposal regulations and local community reuse plans (US Air Force, 1993). Based on the approved final land reuse plan, Site OT45 is proposed to be reused as a commercial property (i.e., dedicated to convention/tourist services) (US Air Force, 1993). The planned use of this site will result in unrestricted public access, but actual occupancy will be nonresidential, intermittent in frequency and of a short duration. This is important because the final risk-based strategy need only protect industrial receptors if the contamination does not migrate appreciable distances over time.

Groundwater use information also was collected during the site investigation at Site OT45. The water supply for Base facilities is currently derived from seven on-Base groundwater wells drilled and installed within the shallow aquifer. Groundwater use restrictions have been imposed on areas where shallow groundwater contamination exists or is suspected to exist. The approved land reuse plan calls for replacing the on-Base water supply system with local domestic water supply systems. As a result, there is no need (or plan) to extract groundwater from the shallow aquifer at Site OT45 (or any area on-Base) to meet future water supply demands. This is important because it will provide the basis for securing approval of alternate target cleanup goals for groundwater at the site.

TIER 1 SCREENING EVALUATION

After sufficient analytical data and other relevant site information were collected, a Tier 1 screening evaluation was performed for Site OT45. According to the final land use plan for Wurtsmith AFB, which was approved by the Oscoda Township Board of Trustees, the expected future use of Site OT45 will be commercial (US Air Force, 1993). MDEQ risk-based guidance specifies that industrial cleanups will generally apply at "sites where the uses of the property are expected to be limited at the completion of the remedial action" (MDEQ, 1995b). Industrial cleanup criteria are appropriate for sites where the current and/or planned activities to be conducted onsite can be described as commercial in nature. Generic industrial/commercial cleanup criteria developed by the MDEQ were used as screening tools to identify which contaminants in soil and groundwater at Site OT45 required further evaluation.

It also was determined that because of potential off-Base use of shallow groundwater, generic residential criteria should be applied to groundwater at the Base boundary. Generic residential criteria were used to determine which compounds would require further fate and transport analysis to evaluate potential risks to downgradient, off-Base receptors. It is important to note that residential criteria do not need to be met onsite to protect potential industrial/commercial workers.

Table A.2 presents a comparison of the maximum detected concentrations of soil contaminants and the health-based generic industrial/commercial criteria. Table A.3 presents a comparison of the maximum detected concentrations of groundwater contaminants and both generic industrial/commercial and residential criteria. Exceedances of screening criteria are shaded on the tables. The generic industrial/commercial soil leaching criteria were exceeded by 1,2,4-trimethylbenzene (TMB) and phenanthrene. These two compounds were retained for streamlined evaluation of the potential impact to groundwater underlying the source area at Site OT45.

No detected concentrations of groundwater contaminants at Site OT45 exceeded the generic industrial/commercial groundwater screening criteria. However, three compounds, 1,2,4-TMB, 1,3,5-TMB, and phenanthrene were detected in groundwater at Site OT45 at concentrations above the generic residential screening criteria. Based on the potential to impact off-Base receptors, these three compounds were retained for streamlined evaluation and analysis.

Nature and Extent of Contaminants

Residual heating oil contamination in smear zone soil at the former UST location may be acting as a limited, but continuing source of groundwater contamination at Site OT45. COPCs in soil conservatively include phenanthrene and 1,2,4-TMB. Soil contamination is limited to an area of approximately 50 feet in diameter around the former UST. Average concentrations of phenanthrene appear to have decreased by an order of magnitude between the 1992 RI (ICF, 1993) and the 1994 risk-based investigation (from 11,000 µg/kg to 565 µg/kg). The significant decrease observed in source area soil concentrations of phenanthrene may be indicative of the positive effects of natural attenuation processes. 1,2,4-TMB soil data were collected during the 1994 risk-based investigation only.

The nature and extent of phenanthrene, 1,2,4-TMB, and 1,3,5-TMB in groundwater was evaluated using previous site investigation data, data collected during the 1994 initial risk-based site investigation, and data collected during an annual sampling event performed at the site in 1995. This annual sampling event occurred after the risk-based site investigation and was the first sampling event of a long-term monitoring plan that was implemented as a recommendation of the draft RAP for Site OT45.

Dissolved concentrations of the three analytes detected above generic residential criteria appear to be rapidly decreasing. Dissolved concentrations of both phenanthrene and 1,3,5-TMB decreased to levels below generic residential cleanup criteria between the 1994 risk-based investigation and the 1995 annual sampling event. As a result, 1,2,4-TMB is the only remaining groundwater contaminant that may ever pose a risk to off-site receptors. Additionally, concentrations of 1,2,4-TMB appear to have decreased by approximately 40 percent between the 1994 and 1995 investigations. Concentrations of 1,2,4-TMB, 1,3,5-TMB and phenanthrene do not appear to have migrated more than 180 feet downgradient from the location of the former UST.

Streamlined Fate and Transport Analysis

A streamlined fate and transport analysis was performed as part of the Tier 1 evaluation to quantify the nature and extent of the two soil contaminants detected above industrial/commercial leaching criteria and the three groundwater contaminants detected above residential screening criteria at Site OT45. Analysis of the two soil contaminants was performed to determine if concentrations of the contaminants in the soil could ever generate leachate concentrations in exceedance of the generic industrial/commercial groundwater cleanup criteria. Analysis also was performed to determine if contaminants detected at the site in 1994 above the generic residential groundwater criteria could migrate to the Base boundary at concentrations above the generic residential criteria.

Leaching from Soils

Phenanthrene and 1,2,4-TMB were measured in saturated soils in 1994 at concentrations above the respective industrial/commercial soil leaching criteria (Table A.2). However, concentrations of phenanthrene and 1,2,4-TMB measured in groundwater during the 1994 sampling event suggest that the MDEQ's formula for calculating the generic soil leachate criteria may underestimate the allowable concentrations of soil contaminants that are protective of underlying groundwater. Maximum concentrations of both soil contaminants detected in groundwater samples collected in 1994 were below generic industrial/commercial groundwater cleanup criteria (Table A.3).

A more reasonable approximation of the desorption of phenanthrene and 1,2,4-TMB from saturated soils into groundwater at Site OT45 was developed using a simple equilibrium partitioning relationship. The most common equilibrium model used to describe the amount of contaminant that will remain sorbed to the soil and the amount of contaminant that will dissolve into groundwater is the distribution partition coefficient (K_D). The linear distribution partition coefficient is calculated by multiplying the chemical's solubility in water normalized for total organic carbon content (K_{OC}) and the fractional organic carbon content (f_{OC}) of the soil matrix.

Leaching from saturated soils into groundwater was simulated for Site OT45 using a K_D -based equilibrium relationship that accounts for groundwater movement through the affected soil over time. Uncontaminated groundwater flows into the contaminated volume of saturated source soils at the linear velocity of the shallow aquifer. Contaminants sorbed to the soil matrix would leach from the soil into the uncontaminated groundwater, which would then flow from the downgradient edge of the contaminated source soils. The amount of contaminant that would leach from the source soils into each new volume of uncontaminated groundwater depends upon the residual concentration of contaminant in the soil and the chemical-specific K_D .

These calculations were calibrated by matching maximum 1992 soil concentrations of phenanthrene (sorbed mass) to maximum 1992 groundwater concentrations of phenanthrene (dissolved mass). The amount of contaminant that was predicted to have partitioned from the soil and dissolved into groundwater was in good agreement with 1992 groundwater analytical results. This simple relationship was then used to predict the amount of phenanthrene that should have been measured in soil and groundwater

during the 1994 and 1995 sampling events (i.e., 690 and 1040 days from the 1992 sampling event). Changes in 1,2,4-TMB groundwater concentrations measured as part of the 1994 and 1995 sampling events were used to verify the reasonableness of this calculation. The predicted concentrations of phenanthrene and 1,2,4-TMB were in good agreement with the maximum concentrations measured in groundwater in 1994 and 1995.

These calculations indicate that both soil COPCs should have been reduced below the generic industrial/commercial soil leaching criterion in late 1994 or early 1995. A limited soil sampling compliance event has been recommended as a means of documenting that onsite residual soil contamination does not pose a threat to underlying groundwater.

Transport in Groundwater

Two lines of evidence were developed to show that, although a few petroleum hydrocarbon compounds detected in groundwater exceeded generic residential criteria at Site OT45, none would migrate to the Base boundary in excess of the residential screening criteria. The first line of evidence is the decreasing concentrations of compounds over time. As shown in Table A.4, the concentrations of phenanthrene, 1,2,4-TMB, and 1,3,5-TMB have been decreasing rapidly. Phenanthrene and 1,3,5-TMB were not detected above the generic residential criteria during the 1995 annual sampling event, and are no longer considered a risk to potential off-site receptors. This indicates that 1,2,4-TMB is now the only fuel hydrocarbon compound in groundwater at Site OT45 that exceeds generic residential criteria. Based on the contaminant decreases observed to date, it is anticipated that 1,2,4-TMB will be attenuated to below the residential criteria within 1 year. The rapid decrease of contaminant concentrations makes it unlikely that contaminants will reach the base boundary at concentrations in excess of the residential criteria.

The second line of evidence of contaminant natural attenuation is the lack of significant plume migration over time. Field data on groundwater velocity, the estimated site-specific biodegradation rate for 1,2,4-TMB, and the estimated contaminant velocity were used to calculate the distance that 1,2,4-TMB could be expected to travel before biodegrading to below residential groundwater cleanup criteria. It was calculated that concentrations of 1,2,4-TMB would only migrate an estimated additional 10 feet before concentrations drop to below residential criteria. This indicates that 1,2,4-TMB does not pose a risk to potential downgradient receptors.

RISK-BASED SITE CLOSURE

Given the current and planned uses, zoning, and access restrictions enforced at Site OT45, no further action is required to protect human health and the environment. A one-time compliance soil sampling event has been proposed to verify that concentrations of soil COPCs have either dropped below the generic industrial/commercial soil leaching criteria and/or do not pose a threat to underlying groundwater quality by causing elevated dissolved concentrations.

Because no chemical has been detected in groundwater above the most restrictive generic industrial/commercial groundwater criteria that is applicable to onsite media,

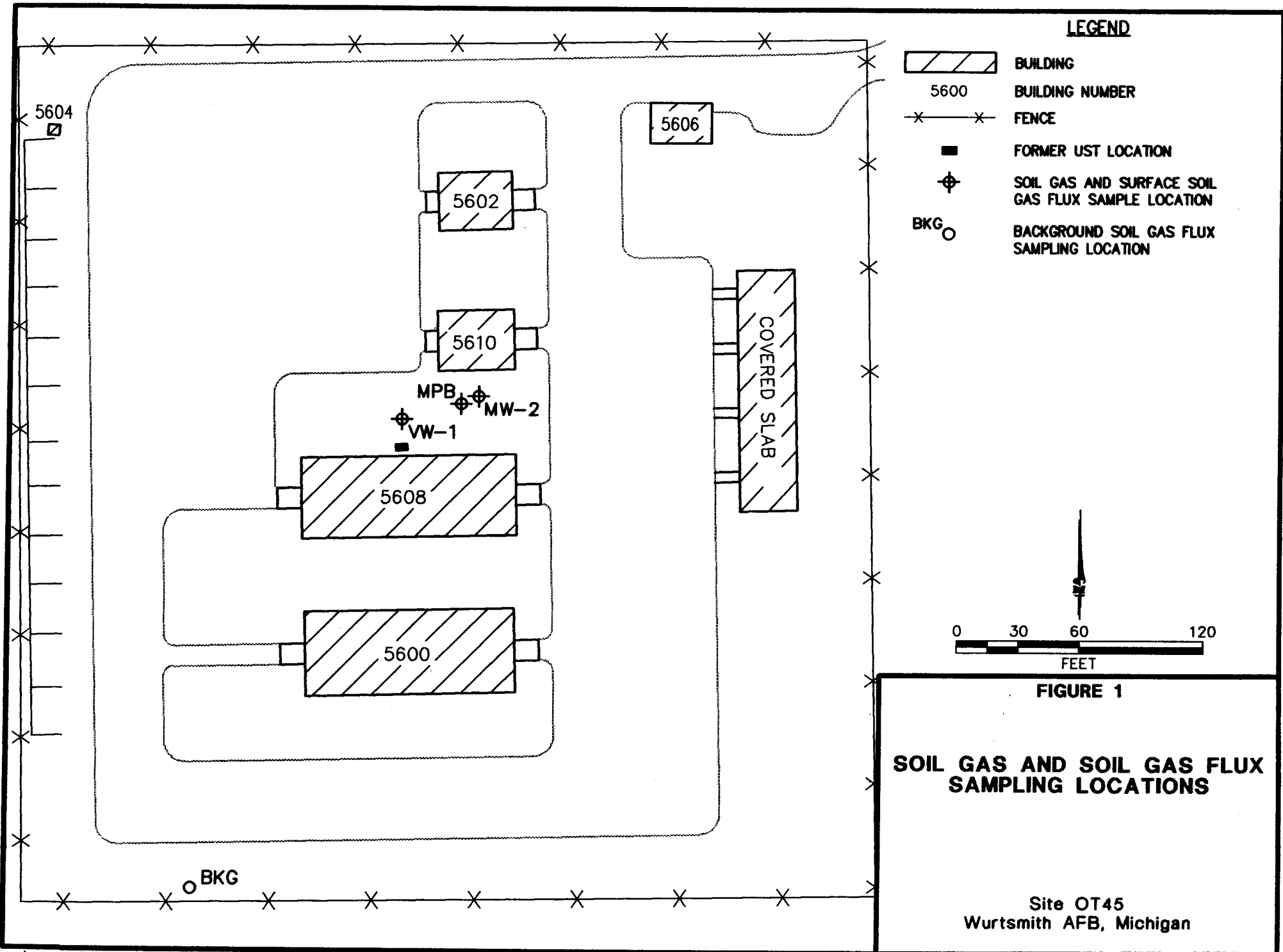
no additional groundwater sampling is necessary at Site OT45 to support a closure decision. However, a limited groundwater sampling event has been recommended to provide analytical data to verify that onsite chemicals are not migrating toward the Base boundary at concentrations in excess of the generic residential groundwater cleanup criteria. This sampling event will also further prove that the conclusion of the FS (i.e., active groundwater remediation is required) was too conservative and would lead to an increase in cleanup cost with no apparent risk reduction benefit.

Regulatory Approval

The draft final second edition of the RAP for the Risk-Based Remediation of Site OT45 was issued to the MDEQ and Region V of the US Environmental Protection Agency (USEPA) for final review in April 1996. MDEQ and EPA approval of the RAP was received in the summer of 1996. Two additional years of monitoring indicate that natural attenuation has now reduced all contaminants of concern to levels which meet industrial cleanup criteria.

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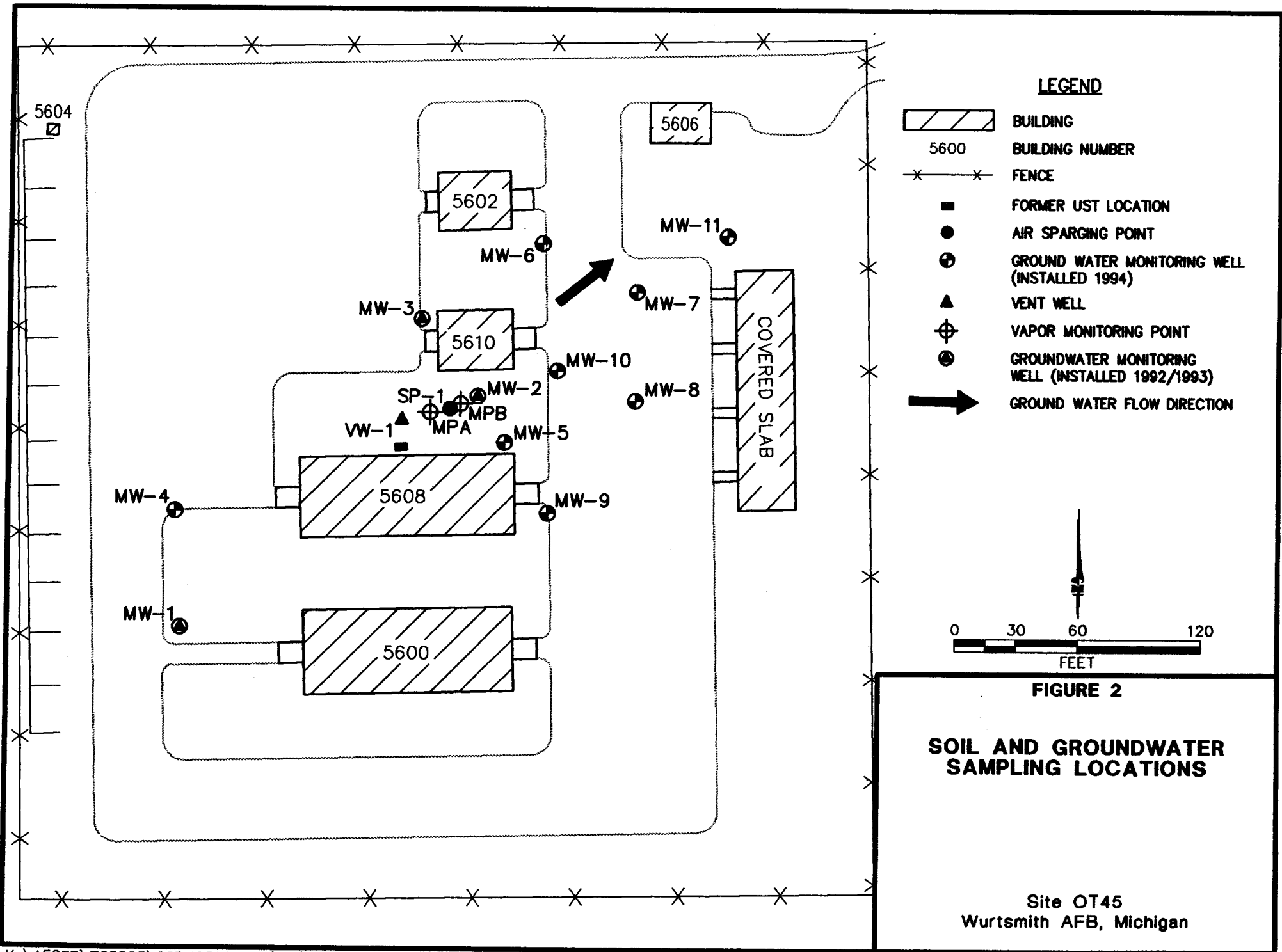


TABLE A.1
FIXED-BASE AND FIELD METHODS BY ANALYTE
SITE 0T45, WURSMITH AFB, MICHIGAN

Analyte	Matrix	Analytical Method	Field or Fixed-Base
Benzene	Soil Gas	TO3	Fixed-Base
Toluene	Soil Gas	TO3	Fixed-Base
Ethylbenzene	Soil Gas	TO3	Fixed-Base
Xylene (Total)	Soil Gas	TO3	Fixed-Base
Petroleum Hydrocarbons	Soil Gas	TO3	Fixed-Base
Total Extractable Hydrocarbons	Soil and Water	M8015	Fixed-Base
Total Volatile Hydrocarbons	Soil and Water	M8015	Fixed-Base
Benzene	Soil and Water	SW8020	Fixed-Base
Toluene	Soil and Water	SW8020	Fixed-Base
Ethylbenzene	Soil and Water	SW8020	Fixed-Base
Xylene (Total)	Soil and Water	SW8020	Fixed-Base
1,2,3-Trimethylbenzene	Soil and Water	SW8020	Fixed-Base
1,2,4-Trimethylbenzene	Soil and Water	SW8020	Fixed-Base
1,3,5-Trimethylbenzene	Soil and Water	SW8020	Fixed-Base
2-Methylnaphthalene	Soil and Water	SW8270	Fixed-Base
Acenaphthene	Soil and Water	SW8270	Fixed-Base
Acenaphthylene	Soil and Water	SW8270	Fixed-Base
Anthracene	Soil and Water	SW8270	Fixed-Base
Benzo(a)anthracene	Soil and Water	SW8270	Fixed-Base
Benzo(a)pyrene	Soil and Water	SW8270	Fixed-Base
Benzo(b)fluoranthene	Soil and Water	SW8270	Fixed-Base
Benzo(g,h,i)perylene	Soil and Water	SW8270	Fixed-Base
Benzo(k)fluoranthene	Soil and Water	SW8270	Fixed-Base
Chrysene	Soil and Water	SW8270	Fixed-Base
Dibenz(a,h)anthracene	Soil and Water	SW8270	Fixed-Base
Dibenzofuran	Soil and Water	SW8270	Fixed-Base
Fluoranthene	Soil and Water	SW8270	Fixed-Base
Fluorene	Soil and Water	SW8270	Fixed-Base
Indeno(1,2,3-cd)pyrene	Soil and Water	SW8270	Fixed-Base
Naphthalene	Soil and Water	SW8270	Fixed-Base
Phenanthrene	Soil and Water	SW8270	Fixed-Base
Pyrene	Soil and Water	SW8270	Fixed-Base
pH	Soil	SW9045	Fixed-Base
Total Organic Carbon	Soil	SW9060	Fixed-Base
Moisture, Percent	Soil	E160.3	Fixed-Base
Phosphorus, Total Orthophosphate (as P)	Soil	E300.0	Fixed-Base
Alkalinity, Total (as CaCO ₃)	Soil	E310.1	Fixed-Base
Nitrogen, Total Kjeldahl	Soil	E351.3	Fixed-Base
Iron	Soil	SW6010	Fixed-Base

TABLE A.1 (Concluded)
FIXED-BASE AND FIELD METHODS BY ANALYTE
SITE 0T45, WURSMITH AFB, MICHIGAN

Compound	Matrix	Analytical Method	Field or Fixed-Base
Benzene	Water	SW8240	Fixed-Base
Toluene	Water	SW8240	Fixed-Base
Ethylbenzene	Water	SW8240	Fixed-Base
Xylene (Total)	Water	SW8240	Fixed-Base
1,2,3-Trimethylbenzene	Water	SW8240	Fixed-Base
1,2,4-Trimethylbenzene	Water	SW8240	Fixed-Base
1,3,5-Trimethylbenzene	Water	SW8240	Fixed-Base
Electrical Conductivity	Water	FCOND	Field
Dissolved Oxygen	Water	FDO	Field
pH	Water	FPH	Field
Redox Potential	Water	FREDOX	Field
Temperature	Water	FTEMP	Field
Iron	Water	H8008	Field
Nitrate	Water	H8039	Field
Nitrite	Water	H8040	Field
Sulfate	Water	H8051	Field
Hydrogen Sulfide	Water	H8131	Field
Iron, Ferrous	Water	H8146	Field
Alkalinity, Total (as CaCO ₃)	Water	H8221	Field
Carbon Dioxide	Water	H8223	Field
Manganese	Water	HMANG	Field
Carbon Dioxide	Water	COU-O2	Fixed-Base
Methane	Water	RSK175	Fixed-Base

^{a/} Source: MDNR (1994C) Interoffice Communication Memorandum #6, Revision 3, Analytical Detection Limit Guidance (dated February 4, 1994).

TABLE A.2
SOIL CONTAMINANT CLEANUP CRITERIA EXCEEDANCES
SITE OT45, WURTSMITH AFB, MICHIGAN

Analytes	Units	Maximum Detected 1994 Concentration	Commercial	Industrial	Commercial/Industrial
			Subcategory IV Direct Contact ^{a/}	Direct Contact ^{a/}	Soil Leaching (20 Times GW Conc.) ^{b/}
1,2,3-Trimethylbenzene	µg/kg	1,400	-- ^{c/}	--	--
			8.50E+06	3.10E+06	
1,3,5-Trimethylbenzene	µg/kg	1,300	6.40E+06	2.30E+06	1,300
2-Methylnaphthalene	µg/kg	7,000	--	--	--
Acenaphthene	µg/kg	380	1.00E+09	8.18E+08	76,000
Benzo(a)anthracene	µg/kg	33	6.80E+05	2.10E+05	96
Benzo(a)pyrene	µg/kg	34	6.80E+04	2.10E+04	59
Benzo(b)fluoranthene	µg/kg	57	6.80E+05	2.10E+05	96
Benzo(g,h,i)perylene	µg/kg	30	5.40E+07	1.60E+07	1,500
Benzo(k)fluoranthene	µg/kg	22	6.80E+06	2.10E+06	960
Chrysene	µg/kg	41	6.80E+07	2.10E+07	9,600
Dibenzofuran	µg/kg	110	--	--	--
Ethylbenzene	µg/kg	160	2.00E+08	7.20E+07	1,480
Fluoranthene	µg/kg	38	1.00E+09	5.40E+08	50,000
Fluorene	µg/kg	550	1.00E+09	5.40E+08	50,000
Indeno(1,2,3-cd)pyrene	µg/kg	32	6.80E+05	2.10E+05	96
Naphthalene	µg/kg	1,400	5.40E+08	1.60E+08	15,000
			5.40E+07	1.60E+07	
Pyrene	µg/kg	180	1.00E+09	3.40E+08	32,000
Toluene	µg/kg	31	4.60E+08	1.60E+08	15,800
Total xylenes	µg/kg	890	1.00E+09	1.00E+09	5,600

Source: MDNR, 1995b.

- ^{a/} Health-protective value to protect workers from long-term, systemic health effects from incidental ingestion and dermal absorption of chemicals in soil.
- ^{b/} Soil leaching criterion that is protective of underlying groundwater quality. Appropriate value calculated as 20 times the industrial groundwater criterion.
- ^{c/} Not available/not applicable.

TABLE A.3
GROUNDWATER CONTAMINANT CLEANUP CRITERIA EXCEEDANCES
SITE OT45, WURTSMITH AFB, MICHIGAN

Analytes	Units	Maximum Detected Concentration 1994	Industrial/Commercial Health-Based Criterion ^{a/}	Residential Health-Based Criterion	Aesthetic Criteria ^{b/}	State Drinking Water Standards ^{c/}
1,2,3-Trimethylbenzene	µg/L	37	-- ^{d/}	--	--	--
			86		--	--
			65		--	--
1,2,3,4-Tetramethylbenzene	µg/L	NA	--	--	--	--
2-Methylnaphthalene	µg/L	230	--	--	--	--
Acenaphthene	µg/L	19	3,800	1,300	--	--
Anthracene	µg/L	5	21,000	7,300	--	--
Benzene	µg/L	1.7	120 ^{e/}	29.37	--	5
Ethylbenzene	µg/L	7.2	2086 ^{e/}	730	74	700
Fluorene	µg/L	26	2,500	880	--	--
Naphthalene	µg/L	150	750	260	--	--
			75		--	--
Toluene	µg/L	4.3	4171 ^{e/}	1,460	790	1,000
Total xylenes	µg/L	23	41714 ^{e/}	14,600	280	10,000

Source: MDNR, 1995b.

^{a/} Health-based values are designed to protect onsite workers whose drinking water is from an onsite groundwater source.

^{b/} Aesthetic values designed to protect against adverse taste and odor impacts. This criterion must be met onsite if groundwater is used as an onsite potable water source and the criterion is more restrictive than the health-based value.

^{c/} The state drinking water standard must be met onsite if groundwater is used as an onsite potable water source, and the standard is more restrictive than the health-based or aesthetic criteria.

^{d/} Not available/not applicable.

^{e/} Value was calculated using the generic industrial cleanup criteria algorithm for groundwater ingestion.

TABLE A.4
DISSOLVED CONCENTRATIONS OF CONTAMINANTS OF INTEREST^{a/}
SITE OT45, WURTSMITH AFB, MICHIGAN

WELLS	COMPOUND	UNITS	ANALYTICAL RESULTS		
			Oct-92	Oct-94	Oct-95
MW-11	1,3,5-Trimethylbenzene	µg/L	NA ^{b/}	5 U ^{c/}	0.5 U
	1,2,4-Trimethylbenzene	µg/L	NA	5 U	0.5 U
	Phenanthrene	µg/L	NA	NS ^{d/}	0.5 U
MW-7	1,3,5-Trimethylbenzene	µg/L	NA	1.3 J ^{e/}	5.4
	1,2,4-Trimethylbenzene	µg/L	NA	4 U	1.8
	Phenanthrene	µg/L	NA	10 U	0.5 U
MW-10 (deep well)	1,3,5-Trimethylbenzene	µg/L	NA	4 U	0.4 U
	1,2,4-Trimethylbenzene	µg/L	NA	4 U	0.4 U
	Phenanthrene	µg/L	NA	10 U	0.5 U
MW-5	1,3,5-Trimethylbenzene	µg/L	NA	19	4.3
	1,2,4-Trimethylbenzene	µg/L	NA	63	15
	Phenanthrene	µg/L	NA	1 J	0.5 U
MPB	1,3,5-Trimethylbenzene	µg/L	NA	17	0.4 U
	1,2,4-Trimethylbenzene	µg/L	NA	36	1.5
	Phenanthrene	µg/L	5 U	7 J	0.5 U
VW-1 (W-OT45) ^{f/}	1,3,5-Trimethylbenzene	µg/L	NA	43	2.4
	1,2,4-Trimethylbenzene	µg/L	NA	82	6.4
	Phenanthrene	µg/L	25 U	19	0.5 U
MW-2	1,3,5-Trimethylbenzene	µg/L	NA	4 U	8.7
	1,2,4-Trimethylbenzene	µg/L	NA	4 U	48
	Phenanthrene	µg/L	1500	70	6 J
MW-3	1,3,5-Trimethylbenzene	µg/L	NA	4 U	NS
	1,2,4-Trimethylbenzene	µg/L	NA	4 U	NS
	Phenanthrene	µg/L	5 U	NS	NS
MW-6	1,3,5-Trimethylbenzene	µg/L	NA	4 U	NS
	1,2,4-Trimethylbenzene	µg/L	NA	4 U	NS
	Phenanthrene	µg/L	NA	10 U	NS
MW-8	1,3,5-Trimethylbenzene	µg/L	NA	4 U	NS
	1,2,4-Trimethylbenzene	µg/L	NA	4 U	NS
	Phenanthrene	µg/L	NA	10 U	NS

TABLE A.4 (Concluded)
DISSOLVED CONCENTRATIONS OF CONTAMINANTS OF INTEREST^{a/}
SITE OT45, WURTSMITH AFB, MICHIGAN

WELLS	COMPOUND	UNITS	ANALYTICAL RESULTS		
			Oct-92	Oct-94	Oct-95
MW-9	1,3,5-Trimethylbenzene	µg/L	NA	4 U	NS
	1,2,4-Trimethylbenzene	µg/L	NA	4 U	NS
	Phenanthrene	µg/L	NA	NS	NS
MW-1	1,3,5-Trimethylbenzene	µg/L	NA	4 U	NS
	1,2,4-Trimethylbenzene	µg/L	NA	4 U	NS
	Phenanthrene	µg/L	5 U	10 U	NS
MW-4	1,3,5-Trimethylbenzene	µg/L	NA	4 U	0.4 U
	1,2,4-Trimethylbenzene	µg/L	NA	4 U	0.4 U
	Phenanthrene	µg/L	NA	NS	0.5 U

^{a/} The contaminants reported in this table exceed generic residential groundwater cleanup criteria but not industrial/commercial groundwater cleanup criteria.

^{b/} NA = Data not available for comparison.

^{c/} U = Analyte not detected above method detection limit.

^{d/} NS = Not sampled.

^{e/} J = Estimated value.

^{f/} Temporary sampling location used during the 1992 investigation (ICF, 1993).

CASE STUDY B
KC-135 CRASH SITE
WURTSMITH AFB, MICHIGAN

INTRODUCTION

Parsons Engineering Science, Inc. (Parsons ES) was retained by the United States (US) Air Force Center for Environmental Excellence (AFCEE) to prepare a remedial action plan (RAP) for the risk-based remediation of soil and groundwater contaminated with JP-4 fuel hydrocarbons at the KC-135 Crash Site at Wurtsmith Air Force Base (AFB), Oscoda, Michigan (the Base). The purpose of the RAP was to develop and describe a recommended remedial action to be implemented at the KC-135 Crash Site that met the requirements of the State of Michigan Department of Environmental Quality (MDEQ).

As described in the main text of this handbook, risk-based remediation is designed to combine natural physical, chemical, and biological processes with low-cost source reduction technologies such as *in situ* bioventing, as necessary, to economically reduce potential risks to human health and the environment posed by petroleum releases. The RAP was prepared as part of a multi-site initiative sponsored by AFCEE to develop this handbook on how best to implement risk-based corrective actions (RBCAs) at fuel-contaminated sites.

REGULATORY FRAMEWORK

The MDEQ has adopted a tiered, risk-based approach to the remediation of petroleum hydrocarbon contaminated sites that is similar to the American Society for Testing and Materials (ASTM) RBCA process and Air Force strategy. This approach allows for the establishment of site-specific corrective action requirements based on an analysis of potential receptor exposures to chemical contamination at or migrating from the release site. Generic cleanup criteria (developed by the MDEQ) and site-specific chemical fate and receptor exposure data are used to identify the most cost-effective remedial approach.

The first level of evaluation in the MDEQ's approach is a Tier 1, or screening-level, assessment where contaminant concentrations measured in site media are compared to MDEQ-defined, non-site-specific target concentration goals, which are based on land use and conservative exposure assumptions. These concentration goals are also known as risk-based screening levels (RBSLs). The MDEQ (1995a and 1995b) has defined three types of generic (i.e., non-site-specific) cleanup criteria based on current and foreseeable land use. Generic cleanup criteria have been defined for unrestricted (i.e., residential), industrial, and commercial land use assumptions. The generic cleanup criteria were developed by the MDEQ using standardized algorithms designed to be protective of human health under each of the three land use scenarios. As presented in Section 3 of the handbook, some states have developed their own screening criteria, making the development of Tier 1 RBSLs unnecessary. The State of Michigan is a good example of where the state regulatory agency has already defined Tier 1 RBSLs, making it easy and very simple to perform a Tier 1 evaluation.

The generic cleanup criteria or RBSLs are used to identify which, if any, contaminants and environmental media may warrant additional evaluation or remediation to protect human health and the environment. If measured site concentrations do not exceed the applicable generic cleanup criteria, no additional

remedial action will be necessary other than maintaining the land use in accordance with the exposure assumptions used to derive the generic cleanup goals. However, in the event that measured site concentrations exceed the applicable generic cleanup criteria a more comprehensive, (i.e., Tier 2) evaluation may be pursued.

A Tier 2 evaluation is more comprehensive than a Tier 1 analysis because it requires quantitative contaminant fate and transport calculations and possibly the development of site-specific remediation goals or site-specific target levels (SSTLs) based on site-specific exposure assumptions. The State of Michigan allows the development of SSTLs if warranted. Refer to Section 3.2 of the handbook for further discussion on the development of SSTLs. The quantitative Tier 2 chemical fate assessment can be used to determine if any unacceptable exposures could occur at the site over time and whether remediation to generic cleanup criteria is possible using different types of remedial approaches. Although Tier 2 evaluations usually involve more rigorous analysis and may require use of institutional controls or engineered barriers to ensure that exposure conditions do not change over time, they result in a more focused remediation of those contaminants that actually pose a risk to potential receptors. A Tier 2 evaluation will result in the same level of health protection as a Tier 1, because remediation is focused on those elements that pose a risk given site conditions.

SITE BACKGROUND

Operational History

The KC-135 Crash Site is located in the western portion of Wurtsmith AFB in Oscoda, Michigan. A KC-135 aircraft crashed at the site during an attempted landing in October 1988. Approximately 3,000 gallons of JP-4 jet fuel were in the fuel tanks at the time of the crash. An unknown amount of fuel was consumed in the ensuing fire, and the remainder percolated into the ground. Wurtsmith AFB was placed on the 1991 Department of Defense Base Closure and Realignment Commission's list for closure. The Base was officially closed on June 30, 1993.

Previous Investigations

The US Geological Survey (USGS) conducted an initial site investigation during March 1989. The study included a soil gas survey and the installation of two groundwater monitoring wells (Figure B.1). The soil gas survey indicated that soil and groundwater immediately adjacent to and downgradient from the crash site were contaminated with fuel hydrocarbons. Light nonaqueous-phase liquid (LNAPL) was measured in both of the monitoring wells between April 1989 and June 1991. No LNAPL was measured in these wells or in any other monitoring wells during later site investigations. The absence of LNAPL suggests that it may have dispersed within capillary fringe soils.

A remedial investigation (RI) was conducted at the site from December 1992 through April 1993 to determine the vertical and horizontal extent of soil and groundwater contamination in support of developing a RAP for the site (WW Engineering & Science, 1993). Eighteen soil boreholes were drilled from the ground surface to the groundwater table and sampled for chemical analysis at 2.5-foot intervals. Temporary groundwater monitoring wells, which were screened across the

groundwater surface, were installed in each of the 18 soil boreholes and sampled for dissolved benzene, toluene, ethylbenzene, and xylenes (BTEX). Additionally, seven permanent groundwater monitoring wells (five shallow wells and two deep wells) were installed and sampled (Figure B.1). These data were collected to supplement the USGS investigation results.

DEFINING SITE CHARACTERIZATION DATA REQUIREMENTS

In order to make a credible and defensible RBCA decision for this site, an adequate and appropriate site characterization data must be available. Sufficient data must be collected to conduct a quantitative fate and transport analysis, perform an exposure pathways analysis, and evaluate the potential treatability of contaminated media using low-cost remedial technologies and approaches. As part of the risk-based investigation at the KC-135 Crash Site, emphasis was placed on filling data gaps identified during previous investigations and on collecting data relevant to documenting the *in situ* biodegradation of fuel hydrocarbons in soil and groundwater.

After a review of previously collected site data, data gaps and target analytes were identified. Data gaps were determined by reviewing a preliminary conceptual site model (CSM) (Section 4 of the handbook) to identify previously undefined potential contaminant migration pathways. Target analytes were identified based on the chemical constituents of the known contaminant source, JP-4 jet fuel, and the results of previous sampling activities at the site. It was determined that additional soil gas, subsurface soil, and groundwater samples were required to adequately quantify potential contaminant migration pathways and associated risk at the KC-135 Crash Site. Source reduction technology pilot testing, present and future land use, and groundwater use data also were required for the site to facilitate risk-based Tier 1 screening, Tier 2 analysis, and final remedial design.

Based on the chemical composition of JP-4 jet fuel, BTEX and the polynuclear aromatic hydrocarbons (PAHs) were identified at the target analytes for all media at the KC-135 Crash Site. It also was determined that electron acceptor and other groundwater geochemical data would be required to facilitate an evaluation of the potential for natural chemical attenuation of dissolved hydrocarbon contamination.

SITE INVESTIGATION

A field investigation was conducted by Parsons ES at the KC-135 Crash Site during September through November 1994. The following sampling and testing activities were performed by Parsons ES at the site:

- Collection of soil gas samples at three locations;
- Drilling and installation of 10 new permanent groundwater monitoring wells, including one deep groundwater monitoring well;
- Collection of 12 subsurface soil samples from 7 of 12 new soil boreholes for fixed-base analytical evaluation;

- Collection of 48 subsurface soil samples from 12 new soil boreholes for field screening; and
- Collection of 20 groundwater samples from different sampling locations for field and/or fixed-base analytical evaluation.

Figure B.1 shows all of the sampling locations at the KC-135 Crash Site. Field sampling and testing activities are summarized briefly in the following sections.

Soil Gas Sampling

The purpose of soil gas sampling was to confirm the 1989 soil gas survey results that showed a limited extent of subsurface soil contamination (USGS, 1990) and to determine the potential for lateral and upward diffusion of contaminated soil gas at the site. Soil gas samples were collected from the existing monitoring well W404 and from newly installed monitoring wells W408 and W409S (Figure B.1). Each of these wells had screened intervals above the water table, which allowed soil gas to be collected from the capillary fringe. All soil gas samples were screened for fuel hydrocarbons, oxygen, and carbon dioxide using hand-held field instruments. Soil gas samples also were collected and analyzed using the fixed-base, US Environmental Protection Agency (USEPA) analytical method TO-3 for specific volatile chemicals (i.e., the BTEX compounds) and total volatile hydrocarbons (TVH).

Subsurface Soil Sampling

Subsurface soil samples were collected at the KC-135 Crash Site to further delineate the nature and extent of saturated and unsaturated soil contamination at the site. Twelve new soil boreholes were drilled with the goals of expanding the existing groundwater monitoring well network and collecting additional contaminant data. Twelve subsurface samples were collected from 7 of the 12 new soil boreholes. Figure B.1 shows the location of each of these subsurface soil sampling locations, and Table B.1 presents the fixed-base analytical methods used for the analysis of soil samples collected at the site. Ten of the 12 new soil boreholes were completed as permanent, 2-inch-diameter groundwater monitoring wells (W407 through W416).

Groundwater Sampling

Analytical groundwater samples were collected from new wells and previously installed wells shown on Figure B.1 to define the nature and extent of source area and dissolved contamination. Geochemical data relevant to documenting the potential for biodegradation of dissolved hydrocarbon contamination and quantitatively investigating environmental fate and transport also were collected. Table B.1 presents the fixed-base analytical and field methods used for the analysis of groundwater samples collected at the site.

Source Reduction Technology Testing

Two potential source reduction technologies, biosparging and bioventing, were evaluated during the investigation of fuel contaminated sites at Wurtsmith AFB. A single biosparging test well was constructed at another site on Wurtsmith AFB as part

of another risk-based study. Due to significant hydrogeological similarities between the biosparging test site and the KC-135 Crash Site, the test results were deemed appropriate in predicting the effectiveness of biosparging in remediating groundwater contamination at the KC-135 Crash Site. The goal of the biosparging test was to measure the increase in dissolved oxygen (DO) concentrations created by sparging, and to determine the flow rates required for a full-scale biosparging system in the event that this type of remediation was warranted. This test concluded that three sparging wells with a 5- to 7- standard-cubic-foot-per-minute (scfm) injection rate per well would be sufficient to increase DO concentrations by at least 1 milligram per liter (mg/L) in groundwater at the KC-135 Crash Site source area.

A bioventing test also was completed at the second site to determine the ability of injected air to supply oxygen for biological degradation of fuel residuals. However, initial soil gas oxygen concentrations in the source area were greater than 16 percent, indicating that natural diffusion from the atmosphere was already supplying adequate oxygen for the biodegradation of the low levels of fuel residuals remaining in unsaturated soils at the KC-135 Crash Site.

Present and Future Land Use Information

During the field investigation at Wurtsmith AFB, current and future land use information was collected to determine which generic, land-use based, screening criteria (RBSL) would be appropriate for the site. The KC-135 Crash Site was maintained as an active airfield up until Base closure in 1993. Since Base closure, the site has been maintained as an active airfield operated by a private corporation. A land reuse plan has been developed for the site by the US Air Force and the Oscoda, Michigan Township Board of Trustees. Under this approved plan, the KC-135 Crash Site will continue to be maintained as an airfield. This use would continue to restrict public access, and no human occupancy of the site is expected. Areas surrounding the site also are proposed to be maintained for industrial use. This is important because the final risk-based strategy need only protect industrial receptors if the contamination does not migrate appreciable distances over time.

Groundwater Use Information

The water supply for Base facilities is currently derived from seven on-Base groundwater wells drilled and installed within the shallow aquifer. Groundwater use restrictions have been imposed in areas where shallow groundwater contamination exists or is suspected to exist. The approved land reuse plan calls for replacing the on-Base water supply system with local domestic water supply systems. As a result, there is no need (or plan) to extract groundwater from the shallow aquifer at the KC-135 Crash Site (or any area on-Base) to meet future water supply demands. This is important because it will provide the basis for securing approval of alternate target cleanup goals for groundwater.

TIER 1 SCREENING EVALUATION

After sufficient analytical data and other relevant site information were collected, a Tier 1 screening evaluation was performed for the KC-135 Crash Site to identify chemicals of potential concern (COPCs) that could require further evaluation.

According to the final land use plan for Wurtsmith AFB, which was approved by the Oscoda Township Board of Trustees, the expected future use of the KC-135 Crash Site will be as an airfield (US Air Force, 1993). MDEQ (1995b) risk-based guidance specifies that industrial cleanups will generally apply at "sites where the uses of the property are expected to be limited at the completion of the remedial action." Industrial cleanup criteria are appropriate for sites where the current and/or planned activities to be conducted onsite can be described as industrial or commercial in nature. However, the most conservative cleanup criteria possible for the KC-135 Crash Site are residential cleanup criteria. The use residential criteria was appropriate because the extent of potential downgradient contaminant migration had not been quantified. In order to protect any potential downgradient receptors, residential criteria were applied at the site. Residential cleanup criteria developed in MDEQ (1995a) Operational Memorandum #8, Revision 4, were used as conservative Tier 1 screening criteria to identify which contaminants in soil and groundwater at the KC-135 Crash Site required further evaluation. In the cases where residential screening criteria were more stringent than method detection limits (MDLs), MDLs were used as the comparison criteria.

No contaminants were detected in soils at concentrations that exceeded the Tier 1 screening levels. As a result, no soil COPCs were identified at the KC-135 Crash Site. Specific chemicals that were measured in groundwater in either 1992 or 1994 at concentrations that exceeded any of the generic residential cleanup criteria are presented in Table B.2. The criteria that were exceeded are shaded on the table. Health-based, aesthetic, and groundwater/surface water interface (GSI) residential groundwater criteria are included in the table. The GSI cleanup criteria defines the concentration of a contaminant that can remain in soils adjacent to surface water and not present a threat to surface water quality as a result of leaching. The COPCs in groundwater were BTEX and naphthalene. All of these compounds were included as groundwater COPCs based on data from 1992 and 1994. Naphthalene was considered a groundwater COPC only because concentrations above generic residential GSI cleanup criteria were measured onsite. Naphthalene is not likely to represent an actual chemical threat because no surface water bodies are located at or near the site. Compounds measured at the site at concentrations that did not exceed the most restrictive generic residential screening criteria were not carried forward for further analysis. This is one of the prime advantages of the Air Force strategy; the analysis is focused on potential "risk-drivers" only, rather than all detected chemicals.

TIER 2 ANALYSIS

A Tier 2 analysis was performed after the Tier 1 evaluation to quantify the nature and extent of COPCs as well as contaminant fate and transport. Site-specific target levels (SSTLs) were not developed during this Tier 2 analysis. The State of Michigan has already defined less restrictive cleanup criteria for industrial sites. As a result, the focus of the Tier 2 analysis was to determine if the generic industrial criteria could be achieved in a relatively short time frame at an acceptable cost. This approach included a determination of what receptor exposure pathways are or could be completed at the site and determining if any imminent risks exist at the site.

Nature and Extent of COPCs

The nature and extent of the compounds identified as COPCs were evaluated using previous site investigation data and the data collected during the 1994 risk-based site investigation. Dissolved groundwater contamination has migrated 600 feet downgradient from the source area to well W411, and appears to be limited to a region extending from the source area to the northern edge of the aircraft runway. The 1994 location of the BTEX plume at the site is shown in Figure B.2. A comparison of 1992 sampling data to 1994 data indicated that the leading edge of the plume has stabilized. Sampling also indicated that a 63-percent reduction in dissolved BTEX concentration occurred in the plume over this 2-year period.

Fate and Transport Analysis of COPCs

The fate of the COPCs identified in groundwater at the KC-135 Crash Site, based on their chemical characteristics and site-specific characteristics, was examined in detail. Emphasis was given to documenting the effects of natural physical, chemical, and biological processes on contaminant mass, concentration, persistence, toxicity, and mobility. The first step in the fate and transport analysis was an exposure pathways analysis. The objective of this assessment was to revise the preliminary CSM to determine which, if any, receptor exposure pathways are complete (USEPA, 1988). Pathways where contaminants are released and may migrate within the environment to potential receptor exposure points were evaluated. Incomplete exposure pathways and those that pose a negligible risk to receptors were eliminated from further consideration. The remedial requirements for the KC-135 Crash Site were developed to address only chemical contamination that may pose an actual risk to human health and/or the environment.

The results of the site-specific exposure pathways screening assessment indicated that the only pathway that may be completed at this site involves potential future off-Base receptor exposure to contaminated groundwater. This exposure pathway was retained based on an extremely conservative, qualitative evaluation of contaminant transport in groundwater. A quantitative fate and transport analysis of contaminated groundwater then was performed using monitoring data and the numerical groundwater flow and contaminant transport model Bioplume II. The effects of transformation processes and other contaminant characteristics that influence contaminant concentration, mass, mobility, persistence, and toxicity were factored into this numerical analysis. The results of the quantitative modeling confirmed that the contaminant plume was at a steady state and was anticipated to recede in the future. Figure B.3 illustrates the reductions in BTEX concentrations predicted to occur over the next 8 years at the KC-135 Crash Site. Based on the results of this site-specific analysis, the off-Base migration pathway was not retained for further analysis.

The conclusions of the quantitative, site-specific exposure pathways analysis were important for two reasons. First, the analysis demonstrated that, even under extremely conservative assumptions, the concentrations of COPCs in groundwater at the site did not pose a risk to human health or the environment because no potential receptor exposure pathway is or is likely to be complete. This is important because it shows that active remediation is not necessary to minimize or eliminate any imminent risks. Second, the assessment showed that onsite groundwater contamination does not pose an

immediate threat to downgradient media. This type of information helped to focus the range of remedial objectives and requirements.

PROPOSED TYPE OF CLEANUP

Given the current and planned land uses, zoning, and access restrictions enforced at the KC-135 Crash Site, it was decided to pursue implementation of remedial actions that would achieve the generic industrial cleanup criteria for all COPCs. It also is possible that the remedial action could reduce site concentrations to below generic residential cleanup criteria over time, however, this is not the target remedial goal for the site. Because the quantitative Tier 2 analysis completed for the site did not indicate any imminent risk at the site, it was determined that the generic industrial criteria were adequate cleanup goals, and no interim actions were required to protect human health and/or the environment. Additionally, it was determined that the generic industrial criteria could be met in an appropriate timeframe at an acceptable cost. This made the development of SSTLs unnecessary for the KC-135 Crash Site.

Generic residential cleanup criteria for groundwater were proposed as the target risk-based cleanup criteria for the downgradient property boundary to protect potential offsite receptors. Implementation of remedial actions that would attain residential cleanup criteria at the site was neither a requirement nor a goal of the RBCA. However, at the request of MDEQ, the effectiveness of different remedial technologies and approaches in achieving residential cleanup criteria at the property boundary (and over time for the entire site) were qualitatively considered when developing remedial alternatives for the site. A comparison of residential and industrial cleanup criteria is shown in Table B.2.

DEVELOPMENT OF REMEDIAL ALTERNATIVES

After it was determined that MDEQ's (1995b) generic industrial criteria would be the appropriate cleanup standards for the site, three possible remedial alternatives were developed. All three of the alternatives were designed to meet the generic industrial criteria, albeit within different time frames and at different costs. The following remedial techniques were evaluated for inclusion in the remedial alternatives:

- Land and groundwater use controls;
- Public education;
- Intrinsic remediation of soil and groundwater contamination with long-term monitoring;
- Biosparging in the source area;
- Groundwater extraction in the source area with activated carbon treatment; and
- Limited bioventing in dewatered soils.

Data from pilot testing of the bioventing and biosparging technologies performed during the risk-based site investigation were used to quantitatively estimate the costs

and effectiveness of these technologies. Intrinsic remediation potential was quantified through analysis of geochemical data collected during the site investigation at the KC-135 Crash Site. A Bioplume II model, created for the site during the Tier 2 analysis, was used to quantitatively estimate groundwater contaminant attenuation and migration at the site under different remedial scenarios.

Three remedial alternative were formulated from the possible remedial techniques: Alternative 1 - Intrinsic Remediation with Long-Term Monitoring and Land and Groundwater Use Controls; Alternative 2 - Biosparging in Source Area, Intrinsic Remediation with Long-Term Monitoring, and Land and Groundwater Use Controls; and Alternative 3 - Limited Groundwater Extraction and Treatment, Air Injection Bioventing, Intrinsic Remediation with Long-Term Monitoring, and Land and Groundwater Use Controls. All three of the alternatives were evaluated in terms of effectiveness, implementability, and cost. A summary of this evaluation is shown in Table B.3.

RECOMMENDED REMEDIAL ALTERNATIVE

Alternative 1 (Intrinsic Remediation with Long-Term Monitoring and Land and Groundwater Use Controls) was recommended for the remediation of the KC-135 Crash Site based on its expected effectiveness in attaining generic industrial (and eventually generic residential) cleanup criteria, its relative simplicity with respect to technical and administrative implementation, and its low overall cost.

Historical decreases in contaminant concentrations and conservative fate and transport modeling indicate that intrinsic remediation will achieve a generic industrial cleanup criteria for groundwater in approximately 10-12 years. Given the current and projected land use as an airfield and the conservative estimates of plume migration, no active remediation is required at this site to protect human health or the environment. Bioplume II modeling predicted very limited plume migration, with no chance of off-Base migration. Long-term groundwater monitoring will be used to verify intrinsic remediation and to ensure that contaminants do not migrate to the airfield boundary or Base boundary. Limitations on groundwater pumping at this site should not impose a restriction on future airfield land use or operations. The following sections provide additional detail on the implementation of this alternative.

Regulatory Approval

The draft RAP for the risk-based remediation of the KC-135 Crash Site was issued to the MDEQ and Region V of the USEPA for review in March 1995. After receiving and addressing comments and providing a regulatory presentation in Michigan, MDEQ and USEPA verbally approved the RAP in February 1996.

Long-Term Monitoring

As part of the RAP, a long-term monitoring plan (LTMP) was developed for the KC-135 Crash Site to monitor the implementation and progress of the recommended remedial action. Because no active, engineered remedial technologies were selected for the site, only groundwater monitoring and land and groundwater use controls will be necessary at the site. Long-term groundwater monitoring is essential to verify the

progress of intrinsic remediation. Careful implementation of the LTMP is a key component of the RAP for the site. The LTMP for the site calls for annual groundwater sampling at a total of nine sampling locations, including three sentry wells to track the horizontal and vertical movement of the plume, and a downgradient point-of-action (POA) well (W403) to ensure that contaminants are not moving at a rate that could result in off-Base migration. Due to the large distance that separates the plume from the Base boundary (4,875 feet), a possible point-of-compliance well (W416) will not be sampled unless contaminants are first detected in the POA well. Annual sampling was considered appropriate by all parties given the limited contaminant migration observed from 1992 to 1994. LTMP sampling locations are shown in Figure B.2.

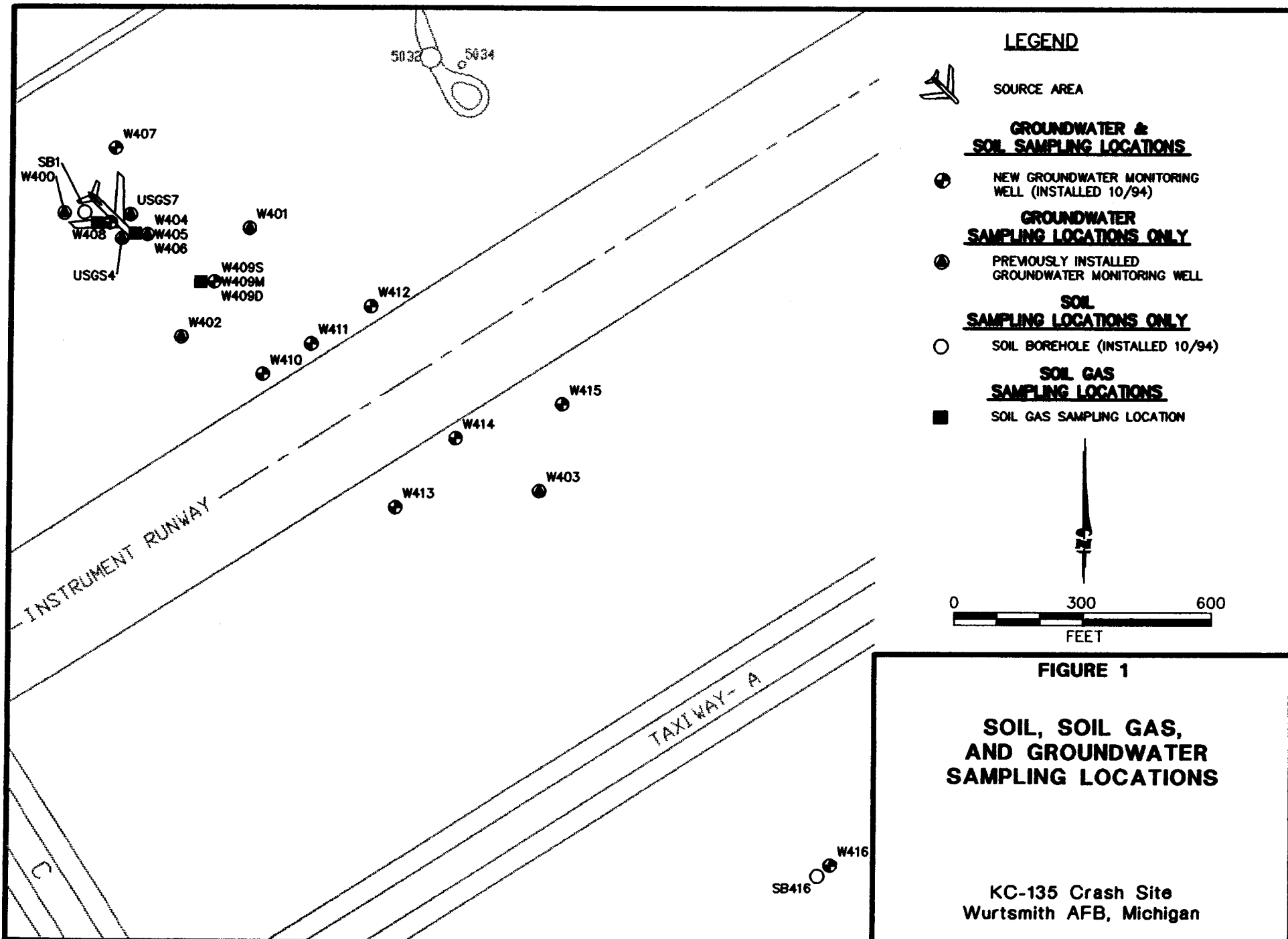
The other component of the LTMP, land use verification, will be accomplished by maintaining communication between the Wurtsmith Air Force Base Conversion Agency (AFBCA), MDEQ, Oscoda Township, and current and future site occupants. The risk-based remediation of the KC-135 Crash Site is based upon an industrial land-use scenario at the site. If land use at the site changes unexpectedly (i.e., the site is released for residential occupancy before generic residential criteria are achieved in 12 years), site conditions and associated risk must be reevaluated accordingly. Visual inspections of the site also will be made during annual groundwater sampling site visits to ensure that no nonindustrial activities are occurring at the site.

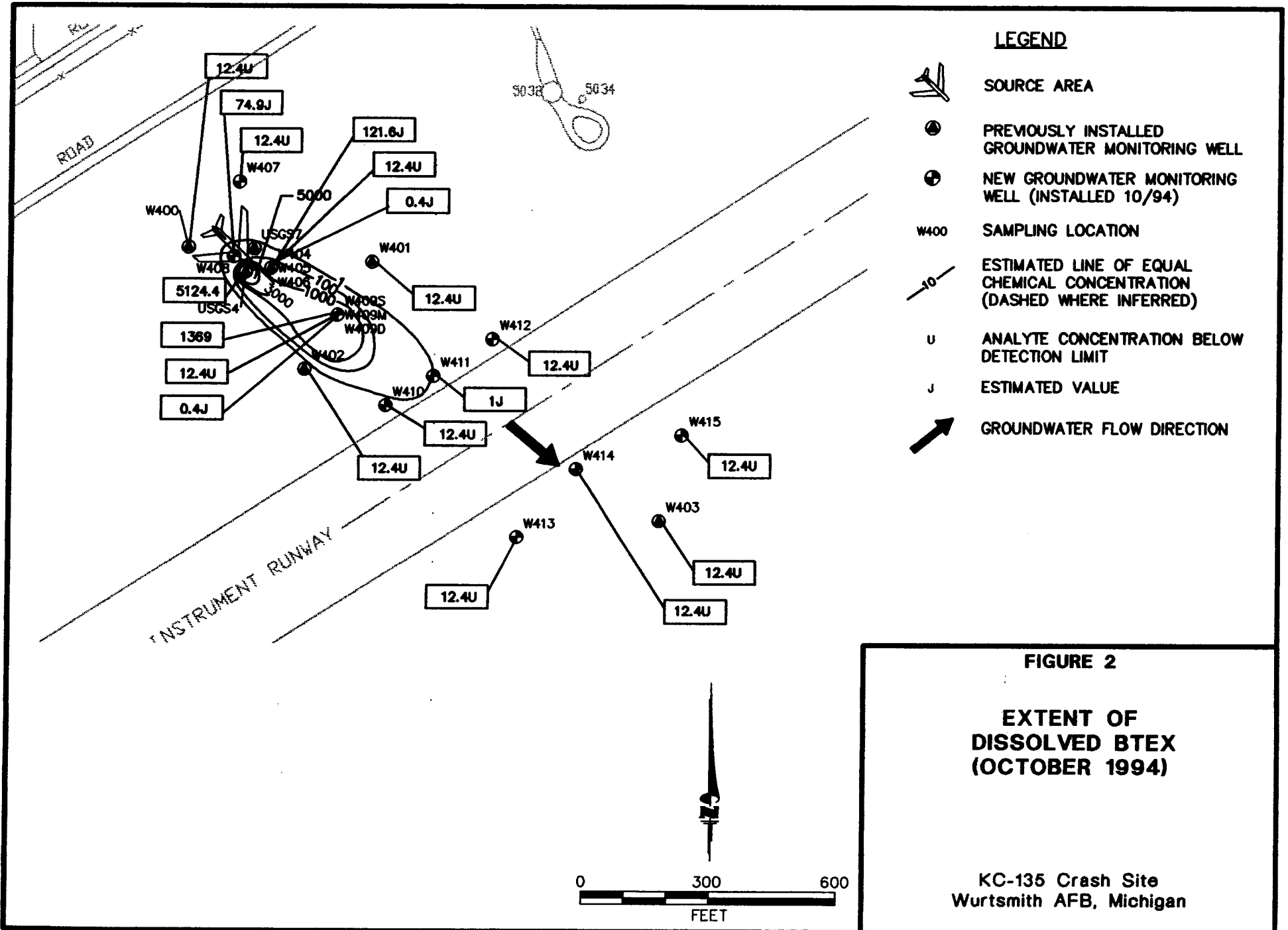
LONG-TERM MONITORING RESULTS

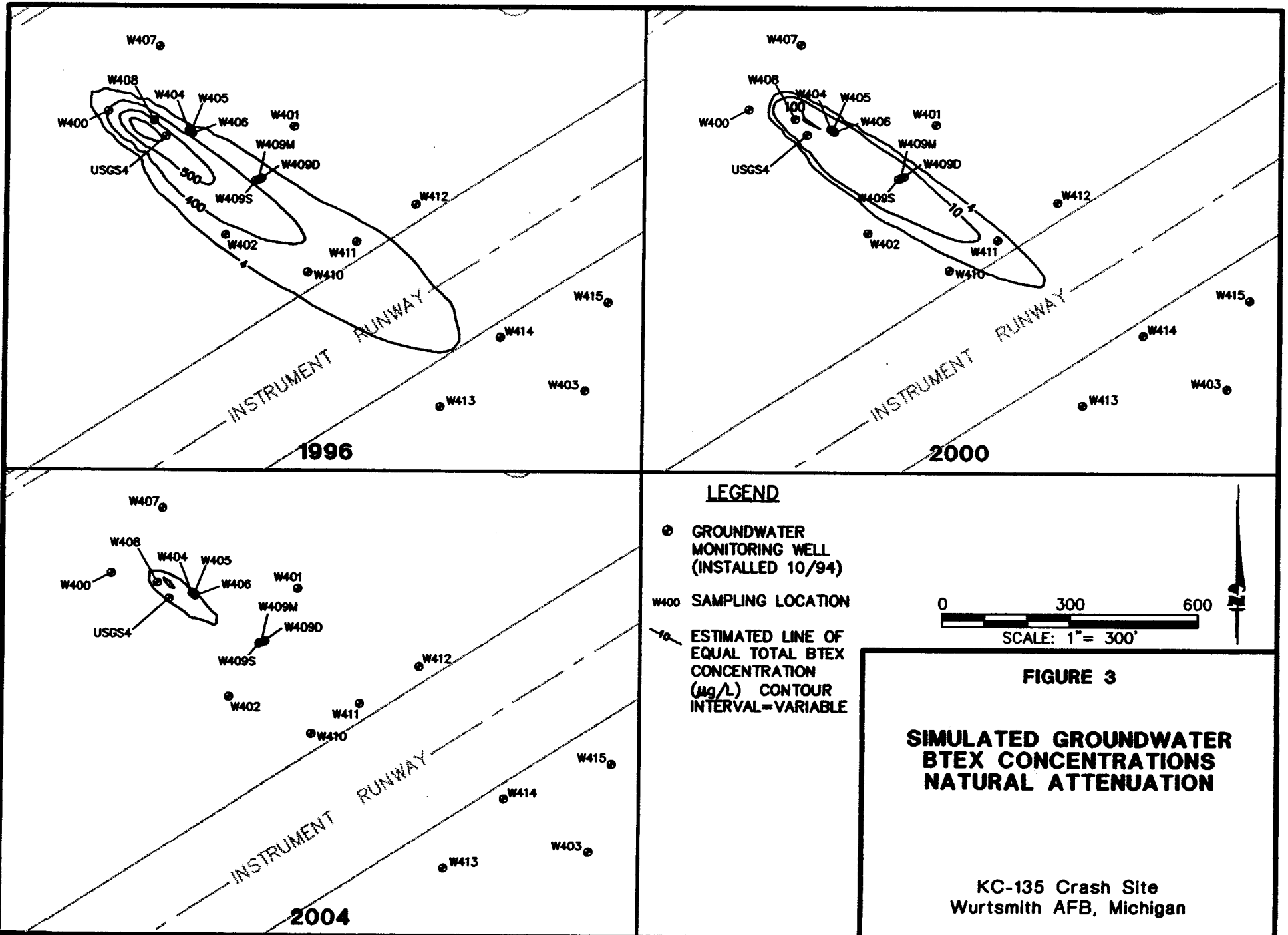
The first round of annual groundwater sampling under the LTMP was completed in October 1995. The sampling results, presented in Table B.4, indicate continued decreases in the BTEX compounds and naphthalene consistent with the conservative predictions of the Bioplume II model. The results of annual groundwater sampling were provided to the AFBCA, MDEQ, and USEPA Region V to update the team on remediation progress and to provide new information for pending land use decisions. Annual sampling will continue until MDEQ generic industrial cleanup criteria have been uniformly attained at the site. Initial contaminant biodegradation and transport calculations suggested that benzene concentrations in groundwater should be reduced below these health-based industrial cleanup criteria in approximately 10-12 years. One-year sampling results, however, indicate that contaminant attenuation at the site may be occurring slightly faster than was conservatively estimated. Based on these 1995 analytical data, it is possible that the site could achieve the generic industrial criteria in shorter period of time than previously estimated.

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**TABLE B.1
FIXED-BASE AND FIELD METHODS BY ANALYTE
KC-135 CRASH SITE, WURTSMITH AFB, MICHIGAN**

Analyte	Matrix	Analytical Method	Field or Fixed-Base
Total Extractable Hydrocarbons (TEH)	Soil and Water	M8015	Fixed-Base
Total Volatile Hydrocarbons	Soil and Water	M8015	Fixed-Base
Benzene	Soil and Water	SW8020	Fixed-Base
Toluene	Soil and Water	SW8020	Fixed-Base
Ethylbenzene	Soil and Water	SW8020	Fixed-Base
Xylene (Total)	Soil and Water	SW8020	Fixed-Base
1,2,3-Trimethylbenzene	Soil and Water	SW8020	Fixed-Base
1,2,4-Trimethylbenzene	Soil and Water	SW8020	Fixed-Base
1,3,5-Trimethylbenzene	Soil and Water	SW8020	Fixed-Base
2-Methylnaphthalene	Soil and Water	SW8270	Fixed-Base
Acenaphthene	Soil and Water	SW8270	Fixed-Base
Acenaphthylene	Soil and Water	SW8270	Fixed-Base
Anthracene	Soil and Water	SW8270	Fixed-Base
Benzo(a)anthracene	Soil and Water	SW8270	Fixed-Base
Benzo(a)pyrene	Soil and Water	SW8270	Fixed-Base
Benzo(b)fluoranthene	Soil and Water	SW8270	Fixed-Base
Benzo(g,h,i)perylene	Soil and Water	SW8270	Fixed-Base
Benzo(k)fluoranthene	Soil and Water	SW8270	Fixed-Base
Chrysene	Soil and Water	SW8270	Fixed-Base
Dibenz(a,h)anthracene	Soil and Water	SW8270	Fixed-Base
Dibenzofuran	Soil and Water	SW8270	Fixed-Base
Fluoranthene	Soil and Water	SW8270	Fixed-Base
Fluorene	Soil and Water	SW8270	Fixed-Base
Indeno(1,2,3-cd)pyrene	Soil and Water	SW8270	Fixed-Base
Naphthalene	Soil and Water	SW8270	Fixed-Base
Phenanthrene	Soil and Water	SW8270	Fixed-Base
Pyrene	Soil and Water	SW8270	Fixed-Base
pH	Soil	SW9045	Fixed-Base
Total Organic Carbon	Soil	SW9060	Fixed-Base
Moisture, Percent	Soil	E160.3	Fixed-Base
Phosphorus, Total Orthophosphate (as P)	Soil	E300.0	Fixed-Base
Alkalinity, Total (as CaCO ₃)	Soil	E310.1	Fixed-Base
Nitrogen, Total Kjeldahl	Soil	E351.3	Fixed-Base
Iron	Soil	SW6010	Fixed-Base
Electrical Conductivity ^{a/}	Water	FCOND	Field
Dissolved Oxygen ^{a/}	Water	FDO	Field
pH ^{a/}	Water	FPH	Field
Redox Potential ^{a/}	Water	FREDOX	Field
Temperature ^{a/}	Water	FTEMP	Field
Iron ^{b/}	Water	H8008	Field
Nitrate ^{b/}	Water	H8039	Field
Nitrite ^{b/}	Water	H8040	Field
Sulfate ^{b/}	Water	H8051	Field
Hydrogen Sulfide ^{b/}	Water	H8131	Field
Iron, Ferrous ^{b/}	Water	H8146	Field
Alkalinity, Total (as CaCO ₃) ^{b/}	Water	H8221	Field
Carbon Dioxide ^{b/}	Water	H8223	Field
Manganese ^{b/}	Water	HMANG	Field
Carbon Dioxide	Water	COU-O2	Fixed-Base
Methane	Water	RSK175	Fixed-Base

^{a/} Analyte measured with direct-reading field instruments.

^{b/} Analyte measured with Hach colorimetric field kit.

TABLE B.2
IDENTIFICATION OF RESIDENTIAL GROUNDWATER CLEANUP CRITERIA EXCEEDANCES
KC-135 CRASH SITE, WURTSMITH AFB, MICHIGAN

COPCs ^{a/}	Range of 1992 Concentrations	Range of 1994 Concentrations	Residential Cleanup Criteria ^{b/}			Industrial Cleanup Criteria ^{c/}	
			Health-Based	Aesthetic	GSI ^{d/}	Health-Based/ARAR ^{e/}	Aesthetic
Benzene (µg/L)				--			--
Toluene (µg/L)							
Ethylbenzene (µg/L)							
Total xylenes (µg/L)			14,600			41,714/10,000	
Naphthalene (µg/L)			260	--		750/NA ^{f/}	--

Note: Shading indicates measured groundwater concentrations exceed potential target remedial criteria.

^{a/} COPCs = chemicals of potential concern.

^{b/} MDEQ, 1995a.

^{c/} MDEQ, 1995b.

^{d/} GSI = groundwater/surface water interface.

^{e/} ARAR = applicable or relevant and appropriate requirement.

^{f/} NA = not available.

TABLE B.3
SUMMARY OF REMEDIAL ALTERNATIVE EVALUATION
KC-135 CRASH SITE, WURTSMITH AFB, MICHIGAN

Remedial Alternative	Effectiveness	Implementability	Present Worth Cost Estimate
Alternative 1			\$159,600
<ul style="list-style-type: none"> -Intrinsic Remediation -Long-Term Monitoring -Land and Groundwater Use Controls 	Contaminant mass, volume, and toxicity will gradually be reduced by intrinsic remediation alone. Concentration of COCs will be below industrial cleanup criteria in approximately 12 years.	Technically simple and easy to implement. Long-term groundwater monitoring for 12 years is required. Current land use restrictions are in place and effective. Requires public education.	
Alternative 2			\$216,900
<ul style="list-style-type: none"> -Biosparging in Source Area -Intrinsic Remediation -Long-Term Monitoring -Land and Groundwater Use Controls 	Similar to Alternative 1, with the addition of biosparging to increase contaminant degradation in the source area. Pilot testing produced significant DO increases. Controversial technology: may not provide effective long-term treatment.	Long-term groundwater monitoring for 8 years is predicted if biosparging can provide uniform oxygen addition to groundwater. Biosparging system will require weekly monitoring. Current land use restrictions are in place and effective. Positive public perception.	
Alternative 3			\$402,100
<ul style="list-style-type: none"> -Limited Groundwater Extraction -Air Injection Bioventing -Intrinsic Remediation -Long-Term Monitoring -Land and Groundwater Use Controls 	Similar to Alternative 1, with the addition of groundwater removal and treatment and air injection bioventing to treat dewatered soils. Generic industrial cleanup criteria for all COCs in groundwater will be met in approximately 3 years once system operation begins. GAC will sufficiently treat groundwater to meet generic residential aesthetic and health-based criteria. Discharge to infiltration trench is recommended.	Long-term groundwater monitoring for 6 years is required. Pump and treat and bioventing systems will require weekly monitoring. A discharge permit may be required for reinjection of treated groundwater. Lengthy lead time required for design and installation of pump and treat system. Contaminated GAC will have to be disposed. Current land use restrictions are in place and effective. Positive public perception.	

TABLE B.4
ACTUAL VS. PREDICTED GROUNDWATER CONCENTRATIONS
KC-135 CRASH SITE, WURTHSMITH AFB, MICHIGAN

WELLS	COMPOUND	UNITS	ANALYTICAL RESULTS			BIOPLUME II PREDICTED CONCENTRATION FOR OCT-95
			DEC-92	OCT-94	OCT-95	
W407	Benzene	µg/L	NA ^{a/}	0.4 U ^{b/}	0.4 U	NO CHANGE - BACKGROUND WELL
	Toluene	µg/L	NA	4 U	0.4 U	
	Ethylbenzene	µg/L	NA	4 U	0.4 U	
	Xylenes	µg/L	NA	4 U	0.4 U	
	TOTAL BTEX	µg/L	NA	12.4 U	1.6 U	
USGS4	Benzene	µg/L	< 500	4.4	0.4 U	3,380
	Toluene	µg/L	3700	2100	1200	
	Ethylbenzene	µg/L	2400	520	410	
	Xylenes	µg/L	9700	2500	1800	
	TOTAL BTEX	µg/L	15800	5124.4	3410	
W404	Benzene	µg/L	< 10	0.4 U	0.4U	80
	Toluene	µg/L	420	1.6 J ^{c/}	1.1	
	Ethylbenzene	µg/L	130	54	23	
	Xylenes	µg/L	700	66	34	
	TOTAL BTEX	µg/L	1250	121.6 J	58.1	
W409S (T-13) ^{e/}	Benzene	µg/L	280	89	8.9	1,000
	Toluene	µg/L	640	770	140	
	Ethylbenzene	µg/L	56	140	69	
	Xylenes	µg/L	360	370	170	
	TOTAL BTEX	µg/L	1336	1369	387.9	
W411 (T-16)	Benzene	µg/L	28	1 J	0.4 U	25 - 50
	Toluene	µg/L	< 1	4 U	0.4 U	
	Ethylbenzene	µg/L	< 1	4 U	0.4 U	
	Xylenes	µg/L	< 3	4 U	0.4 U	
	TOTAL BTEX	µg/L	28	1 J	1.6 U	
W410	Benzene	µg/L	NA	0.4 U	0.4 U	NO CHANGE
	Toluene	µg/L	NA	4 U	0.4 U	
	Ethylbenzene	µg/L	NA	4 U	0.4 U	
	Xylenes	µg/L	NA	4 U	0.4 U	
	TOTAL BTEX	µg/L	NA	12.4 U	1.6 U	
W412	Benzene	µg/L	NA	0.4 U	0.4 U	NO CHANGE
	Toluene	µg/L	NA	4 U	0.9	
	Ethylbenzene	µg/L	NA	4 U	0.8	
	Xylenes	µg/L	NA	4 U	2.4	
	TOTAL BTEX	µg/L	NA	12.4 U	4.1	
W414 (T-17)	Benzene	µg/L	< 1	0.4 U	0.4 U	NO CHANGE
	Toluene	µg/L	< 1	4 U	0.4 U	
	Ethylbenzene	µg/L	< 1	4 U	0.4 U	
	Xylenes	µg/L	< 3	4 U	0.4 U	
	TOTAL BTEX	µg/L	< 6	12.4 U	1.6 U	
W409D	Benzene	µg/L	NA	0.4 U	0.4 U	NO CHANGE
	Toluene	µg/L	NA	0.4 J	0.4 U	
	Ethylbenzene	µg/L	NA	4 U	0.4 U	
	Xylenes	µg/L	NA	4 U	0.4 U	
	TOTAL BTEX	µg/L	NA	0.4 J	1.6 U	

^{a/} NA = Data not available for comparisons.
^{b/} U = Analyte not detected above method detection limit.
^{c/} J = Estimated value.
^{d/} NS = Not Sampled.
^{e/} Temporary sampling location used in the 1992 investigation.

CASE STUDY C

SITE ST-27

CHARLESTON AFB, SC

INTRODUCTION

Parsons Engineering Science, Inc. (Parsons ES) was retained by the United States (US) Air Force Center for Environmental Excellence (AFCEE) to prepare a corrective action plan (CAP) in support of a risk-based remediation decision for soil and groundwater contaminated with fuel hydrocarbons and nonfuel organic compounds at Site ST-27 at Charleston Air Force base (AFB), South Carolina. Site ST-27 consists of several underground storage tanks (USTs) used to store JP-8 jet fuel, motor gasoline (MOGAS), and diesel fuel to support aircraft operations at the base. One or more fuel releases from leaking USTs and fuel transfer lines have contaminated site soil and groundwater with fuel hydrocarbons. In addition to site-related fuel contamination, nonfuel organic compounds from adjacent sites have been measured in soil and groundwater at and immediately upgradient from Site ST-27.

The purpose of the CAP was to document the reasonable potential risks to human health and the environment (i.e., ecological receptors) due to exposure to chemical contaminants originating from Site ST-27 under current conditions. The CAP also estimated the potential risks to future human and ecological receptors due to exposure to chemical contaminants over time, accounting for the effects of natural chemical attenuation processes. Finally, the CAP developed and described a recommended remedial approach for fuel hydrocarbon and nonfuel organic contamination in soils and groundwater at and downgradient from Site ST-27 in accordance with the requirements of the South Carolina Department of Health and Environmental Control (SCDHEC).

Risk-based remediation is designed to combine natural physical, chemical, and biological processes with low-cost source reduction technologies such as *in situ* bioventing, as necessary, to economically reduce potential risks to human health and the environment posed by subsurface petroleum fuel spills. The CAP for this site was prepared as part of a multi-site initiative sponsored by AFCEE to develop a handbook on how best to implement risk-based corrective actions (RBCAs) at fuel-contaminated sites.

REGULATORY FRAMEWORK

The CAP provided the documentation elements specified by the Underground Storage Tank Program of the South Carolina Department of Health and Environmental Control (SCDHEC, 1995) for both Tier 1 and Tier 2 risk-based assessments and evaluations. The SCDHEC guidance outlines a tiered approach for establishing corrective action requirements at specific sites based on an evaluation of potential exposures to chemical contamination at or migrating from a release site. SCDHEC (1995) requires releases to be classified with respect to the time frame in which potential receptors could be exposed to site-related contamination. Site ST-27 was prioritized as a Category 5 site, the lowest priority, indicating that there is no demonstrable threat to human health or the environment, but that some contaminant levels are above the SCDHEC defined Tier 1 levels.

Per SCDHEC regulations, once a release has been initially classified, the site should be subject to a Tier 1 evaluation. As described in Section 3 of this handbook, a Tier 1 evaluation is essentially a screening-level assessment where contaminant concentrations

measured in site media are compared to nonsite-specific (i.e., generic) values. Some states have developed their own screening criteria. South Carolina has developed risk-based screening levels (RBSLs) for a number of chemicals and exposure pathways. Where the SCDHEC has not developed RBSLs for a particular media and exposure pathway (i.e., RBSLs have not been developed by SCDHEC for soil in industrial land use scenarios), RBSLs were developed consistent with SCDHEC methodology.

The RBSLs were used to identify which, if any, contaminants and environmental media may warrant additional evaluation or remediation. If measured site concentrations do not exceed the applicable Tier 1 criteria, no additional remedial actions would be required by the SCDHEC. However, it would be necessary to maintain land use in accordance with the exposure assumptions used to derive the cleanup goals.

In the event that measured site concentrations exceed the applicable Tier 1 RBSLs, a Tier 2 evaluation may be pursued. A Tier 2 evaluation is more comprehensive than a Tier 1 analysis because it requires quantitative contaminant fate and transport calculations and the development of site-specific remediation goals for potential receptor exposure pathways based on reasonable exposure assumptions and actual land use considerations. Tier 2 site-specific target levels (SSTLs) are based on the outcome of a predictive exposure pathways analysis to evaluate current and potential future human health risks and short-term and long-term fate of the contaminants at the site. Tier 2 evaluations usually involve more rigorous analysis and may require use of institutional controls to ensure that exposure conditions do not change over time. A cleanup based on a Tier 2 evaluation should result in a more focused remediation of those contaminants that may actually pose a risk to potential receptors (SCDHEC, 1995).

The CAP was also intended to provide documentation necessary for establishment of a "Ground-Water Mixing Zone" under SCDHEC regulation. Designation of a Ground-Water Mixing Zone allows establishment of a well defined area in which the drinking water standards for groundwater can be exceeded. To use the Ground-Water Mixing Zone exemption several criteria must be met: 1) the contaminant plume must be entirely within the site boundary; 2) an onsite downflow compliance boundary must be established beyond which accepted limits cannot be exceeded; 3) the area of contamination that exceeds the standards may not be allowed to increase prior to attenuation; and 4) removal or containment of the source. In essence, the Ground-Water Mixing Zone allows exceedances of SCDHEC groundwater criteria if there is minimal potential for the groundwater to be part of a completed exposure pathway.

SITE BACKGROUND

Operational History

Site ST-27

The base is located in North Charleston, approximately 10 miles north of the Charleston Harbor and downtown Charleston, South Carolina. Site ST-27 is located in the north-central part of the base, on the western edge of the aircraft maintenance apron and adjacent to the Building 575 maintenance hangar. In previous investigations Site

ST-27 has also been referred to as Solid Waste Management Unit (SWMU) 145. The area immediately around Site ST-27 and Building 575 includes eight other solid waste management units (SWMUs 20-27). The risk-based investigation for the site specifically targeted Site ST-27 (SWMU 145). However, because SWMUs 20-27 are in very close proximity to Site ST-27, the investigation also addressed the areas around the adjacent SWMUs. The area surrounding site ST-27 and Building 575, including the eight SWMUs, is shown in Figure C.1.

Several petroleum USTs have been, or currently are, operated at Site ST-27 (SWMU 145) on the north side of the Building 575 maintenance hangar. In 1977, a 10,000-gallon UST, currently used to store JP-8, was installed in a 6-inch-thick concrete vault. This UST remains in service at the site. A 3,000-gallon UST and a 1,000-gallon UST were used previously at the site to store JP-4 jet fuel and motor gasoline (MOGAS), respectively. Both of these USTs were operated for approximately 30 years before they were removed from service in January 1988. Prior to removing the USTs, the Air Force had suspected that the 3,000-gallon JP-4 jet fuel UST was leaking due to a constant flux of water entering the tank. The suspected leak in the 3,000-gallon UST was confirmed in January 1988, when the tank was removed and soils contaminated with JP-4 jet fuel were discovered. The 1,000-gallon MOGAS tank, which was removed at the same time, reportedly showed no signs of leakage. According to base personnel, some of the most heavily contaminated soils around the former USTs at Site ST-27 were excavated and disposed of during the tank removals [General Engineering Laboratories (GEL), 1988]. The quantity of contaminated soils excavated and removed from the site was not reported.

Two 4,000-gallon fiberglass petroleum USTs were installed at the locations of the former 3,000-gallon and 1,000-gallon USTs at Site ST-27 in April 1988. One of these tanks stored MOGAS, and the other stored diesel fuel. During leak testing in January 1996, it was discovered that both MOGAS and diesel were leaking from the tanks or subsurface transfer lines. The source of the MOGAS contamination was identified and corrected, and this tank is still in service. The source of the diesel leak has not been found and this tank has been emptied and removed from service. The entire site is scheduled to be decommissioned in 1997. The locations of the three existing USTs at Building 575 are shown on Figure C.1.

Previous Investigations

Site ST-27

Several phases of environmental investigations have been conducted at Site ST-27. After the two USTs were removed and a fuel release was confirmed at Site ST-27 (January 1988), the base contracted with GEL of Charleston, South Carolina, to perform an initial hydrogeologic investigation of the site in June 1988. GEL (1988) installed 14 shallow, hand-augered borings and 5 shallow groundwater monitoring wells to assess the impact of the tank leak on soil and groundwater quality. Groundwater contamination was detected in four of the five wells. Groundwater at Site ST-27 is encountered at average depths ranging from 4 to 6 feet bgs. Although no measurable thicknesses of light nonaqueous-phase liquid (LNAPL) were observed, GEL (1988) noted that an oily sheen was present on the surface of groundwater samples collected from two wells.

Following the confirmation of groundwater contamination, Site ST-27 (SWMU 145) was designated as an Installation Restoration Program (IRP) site for continued investigation under a remedial investigation/feasibility study (RI/FS). Versar, Inc. (1992) conducted an IRP Phase II, Stage 2 RI/FS at the base during 1989-1991, which included Site ST-27. Versar, Inc. installed three additional groundwater monitoring wells at Site ST-27 in 1990. Two of the wells were installed in locations presumed to be downgradient from existing wells, while the third was installed with a deep-screened interval to monitor the lower portions of the shallow aquifer. Two soil samples were collected for laboratory analyses from the soil boring for one of the wells. Versar, Inc. (1992) sampled groundwater from the 3 new wells and the 5 existing wells in 1990. Additionally, a sample of LNAPL was collected from one well and analyzed for benzene, toluene, ethylbenzene and xylene (BTEX). The concentrations of each of the BTEX compounds in the collected LNAPL sample were significantly below those expected in "fresh" MOGAS and above those expected in "fresh" JP-4 jet fuel. The two new site-perimeter wells showed no detectable concentrations of BTEX compounds.

EA Engineering, Science, & Technology, Inc. (EA, 1993) performed a supplemental groundwater investigation at Site ST-27 to further delineate the extent of mobile LNAPL on the groundwater table. Four additional shallow groundwater monitoring wells were installed and sampled from May through June 1993. Soil samples were taken from each of the soil borings for the monitoring wells. The headspace of the soil samples was screened in the field for organic hydrocarbon vapors. One soil sample from each soil boring was submitted for laboratory analysis of volatile organic compounds (VOCs), semivolatile organic compounds (SVOCs), total petroleum hydrocarbons (TPH) as gasoline and jet fuel, total lead, and toxicity-characteristic-leaching-procedure (TCLP) metals. EA (1993) detected minor quantities of mobile LNAPL in two wells during their investigation.

Parsons ES (1993) performed preliminary bioventing field tests at Site ST-27 in May 1993, under a separate AFCEE-sponsored effort. Initial testing procedures included a soil/air permeability test and *in situ* microbial respiration tests to determine if the site was suitable for application of the bioventing technology. A soil gas survey was conducted to identify areas where the subsurface soils were oxygen depleted and had elevated fuel hydrocarbon concentrations. based on the soil gas survey results, 1 soil venting well and 4 permanent soil vapor monitoring points were installed to perform the initial pilot testing. Several soil samples were collected from the unsaturated zone and analyzed for total recoverable petroleum hydrocarbons (TRPH), BTEX, nutrients, pH, and other physical parameters. ES (1993) collected three soil gas samples from the vapor monitoring points (VMPs) for analysis of BTEX and total volatile hydrocarbons (TVH). Additionally, portable field instruments were used to measure soil gas composition of oxygen, carbon dioxide, and TVH.

DEFINING SITE CHARACTERIZATION DATA REQUIREMENTS

In order to make a credible and defensible RBCA decision for this site, adequate and appropriate site characterization data must be available. Sufficient data had to be collected to conduct a quantitative fate and transport analysis, perform an exposure pathways analysis and limited risk-assessment, and evaluate the potential treatability of contaminated media using low-cost remedial technologies and approaches. As part of

the risk-based investigation at Site ST-27, emphasis was placed on filling data gaps identified during previous investigations and on collecting data relevant to documenting the *in situ* biodegradation of fuel hydrocarbons in soil and groundwater.

After a review of previously collected site data, data gaps and target analytes were identified. Data gaps were determined by reviewing a preliminary conceptual site model (CSM) (see Section 4 of the handbook) to identify previously undefined potential contaminant migration pathways. Target analytes were identified based on the chemical constituents of the known contaminant sources (JP-4, JP-8, diesel fuel, and MOGAS), and on the results of previous sampling activities at the site. The BTEX compounds, 1,2,4-trimethylbenzene (1,2,4-TMB) and 1,3,5-trimethylbenzene (1,3,5-TMB), naphthalene, and chlorobenzene were identified as target analytes. Additionally, analyses were performed for various SVOCs and other polynuclear aromatic hydrocarbons (PAHs) to determine the concentrations of these compounds in soils and groundwater at the site. To validate and implement a risk-based remedial approach at Site ST-27, additional data were collected by Parsons ES to: (1) establish groundwater flow characteristics, groundwater and soil geochemistry, and aquifer parameters; (2) identify all possible sources that may be contributing to groundwater contamination at the site; (3) evaluate the potential for contaminant source areas to degrade groundwater quality; and (4) identify potential contaminant receptors.

SITE INVESTIGATION

The following sampling and testing activities were performed by Parsons ES from July 1995 through January 1996 at Site ST-27:

- Installation of 9 additional groundwater monitoring wells, including 2 wells screened at different depths, 1 air sparging test well, and 8 new shallow VMPs;
- Collection of 30 subsurface soil samples for laboratory analyses from 15 of the boreholes drilled for the installation of new monitoring wells, the air sparging well, and VMPs;
- Collection of 30 groundwater samples from a total of 22 groundwater monitoring wells, including 13 previously installed wells and the 9 new monitoring wells installed by Parsons ES;
- Collection of three SUMMA[®] canister soil gas samples for quantitative laboratory analyses from three soil VMPs located in close proximity to the suspected fuel source area;
- Collection of 2 samples of "free-phase," mobile LNAPL fuel product from 2 wells for laboratory analyses of fuel composition;
- Using portable field instruments, measurement of soil gas parameters of oxygen (O₂), carbon dioxide (CO₂), and TVH from 6 of the 8 new VMPs (2 of the VMPs contained water on the date of the field measurements); and
- Performance of aquifer slug tests on 10 wells to determine the hydraulic conductivity of shallow and deep zones of the surficial (water table) aquifer.

In addition to these recent field activities, ES (1993) previously conducted a bioventing pilot test at Site ST-27 in May 1993. Field testing, sampling and data collection activities performed during the bioventing study that are relevant to this risk-based remediation study include the following:

- Performance of a limited soil gas survey using seven temporary VMPs to determine soil gas composition for O₂, CO₂, and TVH;
- Installation of 4 permanent VMPs (including a background point) and 1 vertical air injection VW;
- Collection of 3 subsurface soil samples for laboratory analyses from boreholes installed for the VMPs and the VW;
- Collection of 3 SUMMA® canister soil gas samples from 3 different VMPs for fixed-base laboratory analyses;
- Using portable field instruments, measurement of baseline soil gas parameters of O₂, CO₂, and TVH from the 4 VMPs and the VW; and
- Performance of soil air permeability tests and initial *in situ* biorespiration tests.

Figure C.2 shows the locations of the soil samples taken in 1995. Figure C.3 shows the groundwater monitoring wells at site ST-27.

Source Reduction Technology Testing

Two potentially appropriate engineered source-reduction technologies were identified for this site: soil vapor extraction (SVE) and *in situ* bioventing.

Parsons ES conducted a bioventing pilot test at Site ST-27 in May 1993 as part of a separate AFCEE remedial technology testing program. Initial pilot testing indicated that bioventing would be effective in remediating petroleum hydrocarbon contamination in shallow, unsaturated soils at Site ST-27. Based on oxygen utilization rates, an estimated 160 to 1,150 mg of fuel per kg of soil can be degraded each year at this site. Additionally, a recent pilot test at Site SS-41 on Charleston AFB indicated bioventing is highly effective in reducing BTEX contamination in unsaturated soils underlying Charleston AFB.

An SVE pilot test utilizing a horizontal vapor recovery trench and an internal combustion engine (ICE) to treat vapor emissions was initiated in January 1996. The SVE test was run for six months to evaluate the feasibility of removing VOCs and reducing the contaminant mass in the source area using this technology. Significant decreases in total volatile hydrocarbons (TVH) occurred at all vapor monitoring points (VMPs). Based on the results of the initial test, the radius of influence of the single vapor recovery trench was conservatively estimated at 50 feet. However, the radius of vacuum influence was not uniform in all directions due to interrupted flow paths caused by buried tanks and pipelines. To insure that all contaminated soil could be effectively treated, a second horizontal vapor recovery trench was installed at the site in August

1996. Table C.1 contrasts soil gas chemistry at the commencement and completion of the SVE pilot test.

The SVE pilot system was operated between February 1996 and May 1997 as an interim action to remediate the elevated levels of VOCs in soil gas. The results of the SVE interim action are discussed later in the case study.

Present and Future Land Use Information

During the field investigation at the base, current and future land use information was collected to determine which generic, land-use based, Tier I screening criteria (i.e., RBSL) would be appropriate for the site.

Site ST-27 is located in the north-central portion of the base adjacent to Building 575. The entire extent of Site ST-27 and the adjacent SWMUs is within the boundaries of the base, which is surrounded by a chainlink fence. The base is under manned guard 24 hours per day, 7 days per week. The site is located within a designated aircraft maintenance area. Access to this area is restricted. Additionally, the site is capped by 8 to 14 inches of concrete, which precludes direct exposure of onsite receptors (e.g., base personnel) to potentially impacted soils and groundwater.

Most of the area surrounding Site ST-27 and adjacent SWMUs comprises the base industrial aircraft operations and maintenance facilities. This industrial land use supports aircraft maintenance hangars, component repair shops, squadron operations buildings, base operations, a passenger terminal, an air freight terminal, and the Combat Control Squadron building.

The city of North Charleston surrounds Charleston AFB on all sides. The predominant land uses in the city are residential and commercial, with apartment complexes located near Charleston AFB. Commercial developments line the major roadways. Industrial parks also are scattered throughout the city, including a large industrial area located just south of Charleston AFB along the Ashley River. The City of Hanahan, which is located east of North Charleston and Charleston AFB, is primarily residential.

The base is active and is not on any known US Department of Defense closure lists. Future land use changes for some portions of the base are being considered; however, according to the base master plan, the area of Site ST-27 and adjacent SWMUs remain designated as part of the aircraft maintenance and operation facilities. After UST system decommissioning in 1997, it is expected that the land use at and immediately surrounding Site ST-27 will remain industrial. No redevelopment plans currently exist for the site. Therefore, the reasonably expected future land use at and near the site will remain industrial.

Groundwater and Surface Water Use Information

Most drinking water for the Charleston area is not obtained from groundwater sources, because the public water supply system (which utilizes surface water resources) is sufficient to meet current demands. The public water supply system, provided to the base by the Charleston Commission of Public Works, consists of three

intakes that are located on the Edisto River (about 25 miles northwest of the base), Goose Creek Reservoir (about 2 miles northeast of the base), and Foster Creek (about 8 miles north of the base). The base provides no treatment of the water, but does maintain and operate the distribution system under a drinking water supply permit.

However, groundwater within the vicinity of Charleston AFB is used for both industrial and domestic supply purposes. The closest known domestic well is located approximately 2.2 miles downgradient (southwest) from Site ST-27, approximately 1.2 miles downgradient from the southwestern boundary of Charleston AFB. Domestic uses of local deep groundwater resources include home heat pump systems and lawn and garden irrigation.

Ecological Resources

At Site ST-27, the concrete cover and activity level associated with aircraft maintenance in this generally heavily-developed area effectively limit the presence of wildlife populations to the occasional song bird. The only vegetated areas present are two grassy areas covered with maintained grass and forb communities (Figure C.1). These areas do not support trees, and the root zone likely does not extend to the water table. The low structural diversity, the surrounding industrial development, and the managed character of these vegetated area likely limit their attractiveness to wildlife and they are not considered suitable habitat for most species.

TIER 1 SCREENING EVALUATION

As described in Section 3 of this handbook, a Tier 1 screening analysis involves comparing the site-specific contaminant levels to generic levels developed using conservative assumptions. Only those chemicals with contaminant levels above the Tier 1 RBSLs will be subject to further evaluation and potentially to remedial action. After sufficient analytical data and other relevant information were collected, a Tier 1 screening evaluation was performed for Site ST-27 to identify chemicals of potential concern (COPCs).

Methodology

Maximum contaminant levels in soil were compared to RBSLs developed for direct soil contact (i.e., incidental soil ingestion and dermal contact) and to RBSLs developed for the soil contaminant's potential to leach into groundwater. This information is presented in Tables C.2 and C.3. If the maximum measured site concentration exceeded the Tier 1 target concentration, the compound was identified as a COPC.

Tier 1 groundwater RBSLs were compared to the maximum detected site chemical concentrations in groundwater, and those chemicals with concentrations above the RBSLs were identified as COPCs. This information is presented in Table C.4. Note that the Tier 1 analysis and conclusions conservatively considered and addressed the possibility of future unrestricted use of groundwater resources (i.e., unrestricted groundwater use will be assumed for the surrounding off-base and downgradient areas).

For ambient air exposures, the Tier 1 analysis only examined the BTEX compounds. The SCDHEC guidance does not provide ambient air RBSLs for PAHs, stating that

these compounds are not a concern due to their low volatility. Table C.5 compares the air RBSLs and the maximum detected site soil gas concentrations. Those chemicals with maximum site concentrations above the RBSLs were identified as COPCs.

Identified Fuel-Related Chemicals of Potential Concern

Benzene, toluene, ethylbenzene, xylene, naphthalene, chlorobenzene, and 1,3,5-TMB were identified as the site COPCs in soil. These analytes were present in soils at concentrations high enough to potentially cause an exceedance of groundwater RBSLs through soil leaching. It is important to emphasize that soil concentrations did not exceed the RBSLs for ingestion of, or dermal contact with, soils under either a commercial or industrial scenario. Soil concentrations are compared to the direct contact based RBSLs in Table C.2, and to the soil leachability based RBSLs in Table C.3.

Benzene, toluene, ethylbenzene, naphthalene, chlorobenzene, 1,2,4-TMB, 1,3,5-TMB, and *cis*-1,2-dichloroethene (*cis*-DCE) were identified as the groundwater COPCs (Table C.4). All of these except *cis*-DCE are fuel-related compounds thought to be directly associated with releases at Site ST-27. The compound *cis*-DCE is considered a COPC, although its source is not related to Site ST-27.

All BTEX compounds identified in soil gas are potential ambient air COPCs (Table C.5). In addition to being identified as potential COPCs, the concentrations of the BTEX compounds found in soil gas samples, could potentially represent an explosive hazard to Building 575 or subsurface utility systems. The potential explosion hazard was reduced through installation and operation of a soil vapor extraction (SVE) system.

TIER 2 ANALYSIS AND IDENTIFICATION OF CHEMICALS OF CONCERN

Chemicals identified as COPCs during the Tier 1 process should not automatically be considered to be present at levels that pose unacceptable threats to human health. Rather, these exceedances of the screening criteria indicate that further evaluation under more site-specific exposure scenarios is warranted.

As described in Section 3 of this handbook, this second phase of evaluation is described as a Tier 2 evaluation (SCDHEC, 1995) and consists of three steps: 1) establishing site-specific exposure points; 2) establishing site-specific points of compliance (or, as is the case for Site ST-27, points of action (POAs)); and 3) calculating the corresponding site-specific concentrations for the COPCs at the POAs and in the source area, based on the measured and predicted attenuation of the COPCs. As part of the Tier 2 analysis, exposure pathway completion was reexamined to identify only those receptors and exposure pathways that realistically may be completed under actual current or hypothetical future exposure scenarios, considering land uses and the results of the chemical fate and transport assessment.

Nature and Extent of COPCs

The nature and extent of compounds identified as COPCs was evaluated using previous site investigation data and the data collected during the 1995/1996 risk-based site investigation. It was found that soil contamination at Site ST-27 is predominantly

within saturated soils underlying the former location of the 3,000 gallon JP-4 jet fuel UST and the current location of the MOGAS and diesel USTs. Dissolved contamination currently appears to impact an area of less than 2 acres within the immediate vicinity of the fueling dispenser island and canopy on the north side of Building 575. Although recent site data imply a southwesterly groundwater flow (and contaminant transport) direction, historical water table level measurements and compound-specific analytical data suggest that multi-directional groundwater flow may occur at the site. A comparison of compound-specific data at specific sampling locations over time shows that groundwater COPC concentrations generally are decreasing. Figure C.4 presents decreasing concentrations in benzene from 1988 through 1995 as an example of this phenomenon.

Contaminant Fate and Transport

Modeling was performed to predict how COPCs may be transported and transformed over time in LNAPL, soil, and groundwater based on site data and simple mathematical solute transport calculations. This modeling assumed no engineered remedial action is undertaken at Site ST-27. The behavior of COPCs under the influence of natural physical, chemical, and biological processes was quantified to predict: 1) the extent that soil COPCs could leach from contaminated soils and LNAPL into underlying groundwater; 2) to assess the expected persistence, mass, concentration, and toxicity of dissolved COPCs over time at the site; and 3) to estimate potential receptor exposure-point concentrations. Available geochemical data indicated that groundwater COPCs are biodegrading in saturated soils and groundwater. Based on sampling results and modeling, site specific biodegradation rates were estimated for several COPCs. Based on these biodegradation rates the half-life in saturated soil and groundwater for several COPCs was estimated. Benzene's half-life was estimated at 5 years. The half-life of toluene, ethylbenzene, and naphthalene were estimated at 3.5 years, 15 years, and 24 years, respectively. Even in the absence of SVE or bioventing, model simulations suggest that benzene concentrations in the plume core will decrease below the level to prevent further increases in plume size by the year 2005. Benzene concentrations should be reduced by 95 percent by the year 2017. And, benzene should be reduced below the Tier 1 RBSL of 5 µg/L at every sampling location by the year 2028.

The quantitative chemical fate assessment demonstrated that, although the dissolved plume could increase in size and concentration over the next few years, natural chemical attenuation processes will eventually be sufficient to achieve contaminant mass reduction and minimize contaminant mobility. Under the SCDHEC Ground-Water Mixing Rule, a plume does not have to be remediated if it can be demonstrated that the plume is stable and no exposure pathway is likely to be completed. However the fate and transport analysis suggests that it may be desirable to implement some level of source reduction at the site to limit the duration of monitoring requirements (and prevent additional adverse impacts to groundwater quality in the source area from soil and LNAPL sources).

Exposure Pathways Analysis

Exposure pathway completion was reexamined to identify those receptors and pathways that realistically could be completed. Exposure pathway analysis found that

only onsite intrusive and nonintrusive workers could be involved in completed exposure pathways. Based on the available data and modeling results, there are no completed pathways to current or future offsite receptors. The activities of onsite nonintrusive workers are generally confined to the paved areas of the site, and even incidental contact with contaminated soil or groundwater is unlikely. Volatilization from subsurface sources could theoretically pose an inhalation risk to onsite outdoor workers if the concrete apron is removed as part of future land use plans. However, no inhalation risk was predicted for outdoor workers when actual soil gas sampling data was used to calculate risk. No air COPC was predicted to migrate into indoor breathing zones at concentrations above the Tier 1 RBSLs. Therefore, no air exposure pathways will be complete. Site ST-27 has very low groundwater seepage velocity and the potential for multidirectional groundwater flow. These factors tend to limit plume migration and to slow the biodegradation process (i.e., by minimizing the influx of appropriate electron acceptors). However, as discussed above, natural attenuation should be sufficient to limit plume migration by the year 2005, and reduce groundwater COPC concentrations by about 95 percent by the year 2017. No significant plume migration is expected based on conservative modeling results. Therefore, no completed pathway to offsite receptors exists and the site is an excellent candidate for the SCDHEC Ground-Water Mixing Rule.

Development of Site-Specific Target Levels (SSTLs)

As part of the Tier 2 analysis, site-specific target levels are developed for those chemicals detected at concentrations above the Tier 1 RBSLs, and which are involved in a completed or potentially completed exposure pathway. Given the outcome of the Tier 2 quantitative chemical fate and transport assessment, and the revised exposure pathway analysis, onsite intrusive worker exposure to site-related contamination during excavation activities was the only completed exposure pathway. Therefore, this was the only scenario for which health-based Tier 2 SSTLs were developed. In addition, SSTLs for capillary fringe soils were "back calculated" from the groundwater SSTLs to reassess the potential for onsite soils to generate COPC leachate at concentrations equal to or greater than the groundwater SSTLs. Table C.6 presents the soil leaching SSTLs. Table C.7 presents the groundwater SSTLs.

Comparison of Exposure-Point Concentrations to SSTLs

After calculation of the SSTLs, these values were compared to the site-specific contaminant levels, to determine which COPCs would require either remediation to the SSTL levels or further evaluation under a Tier 3 analysis. The maximum detected concentration of soil and groundwater COPCs were conservatively assumed to represent the current and future exposure-point concentrations at Site ST-27. However, it is important to note that the future exposure-point concentrations, for onsite workers engaged in highly intrusive activities, are expected to be significantly lower than the maximum concentrations observed during the 1995/96 sampling events, due to the removal of contaminants via SVE/bioventing and natural attenuation processes.

Table C.6 compares the average detected soil COPC concentrations to the soil leaching SSTLs. All the low-molecular-weight soil COPCs significantly exceed the soil leaching SSTLs (i.e., benzene, toluene, ethylbenzene, xylenes, and chlorobenzene). The leaching calculations suggest that these compounds will continue

to leach from soils and have an adverse impact on underlying groundwater for approximately 8 to 10 years, if no additional remedial actions are taken. In contrast, the heavier hydrocarbon soil COPCs (i.e., 1,3,5-TMB and naphthalene) only slightly exceed their soil leaching SSTLs. These compounds will soon be occluded in soils, and no longer available to leach into underlying groundwater.

Table C.7 compares the maximum detected groundwater COPC concentrations to the health-based groundwater SSTLs. Benzene, toluene, naphthalene, and 1,2,4-TMB concentrations exceed the health-based groundwater reasonable maximum exposure (RME) SSTLs. Benzene is the only groundwater COPC to exceed its health-based SSTL by more than an order of magnitude. All other groundwater COPCs are approaching their health-based SSTLs. The analytical model used to predict the long-term fate of COPCs in impacted media indicates that benzene will be reduced below its health-based SSTL by the year 2017 at every sampling location by natural chemical attenuation processes only.

DEVELOPMENT OF REMEDIAL ALTERNATIVES

based on the initial remedial screening process, and the results of the Tier 2 analysis, several remedial approaches and technologies were retained for the development of remedial alternatives. These technologies were selected to provide a range of passive to more active response actions, all of which will minimize contaminant migration, minimize increases in contaminant concentrations, and prevent receptor exposures. The primary goal of all the candidate alternatives is to remediate Site ST-27 to a point at which no contaminant concentrations exceed Tier 2 SSTLs. The SSTLs for Site ST-27 would be met in slightly different time frames and at different costs under each alternative. The following remedial approaches and technologies were retained for evaluation:

- Long-term soil gas and groundwater monitoring;
- Limited land use controls;
- Groundwater use controls;
- Public education;
- Natural attenuation of soil and groundwater contamination;
- Biosparging in the source area;
- SVE in the source area; and
- Post-SVE bioventing for the treatment of residual soil contamination.

The primary objective of source reduction technologies would be to more rapidly remove contaminants from the shallow groundwater and unsaturated soils near Building 575, the suspected source area at Site ST-27. Accelerating the reduction of source contamination will result in a decrease in the length of time that will be required to attain the appropriate SSTLs for Site ST-27. Additionally, interim source reduction

actions (i.e., SVE), which have been implemented to reduce potential explosive and outdoor inhalation hazards, may allow implementation of more cost-effective approaches. Because natural attenuation has been effectively reducing dissolved contaminants in the groundwater and limiting downgradient migration, this ongoing remediation process can best be enhanced through a reduction of the continuing source of contamination at Site ST-27. Two candidate source soil reduction technologies (interim SVE for the treatment of contaminated soil gas and *in situ* bioventing for the treatment of residual soil contamination) and one *in situ* groundwater treatment technology (biosparging) were retained for additional analysis. Three candidate remedial alternatives were developed from the possible remedial techniques:

Alternative 1 - SVE as an Interim Action, Natural Attenuation, Long-Term Monitoring, and Land and Groundwater Use Controls

Alternative 2 - SVE as an Interim Action, Continuing *In Situ* Bioventing in Source Area, Natural Attenuation, Long-Term Monitoring, and Land and Groundwater Use Controls

Alternative 3 - SVE as an Interim Action, *In Situ* Biosparging in Source Area, Natural Attenuation, Long-Term Monitoring, and Land and Groundwater Use Controls

All three of the alternatives were evaluated in terms of effectiveness, implementability, and cost. A summary of this evaluation is presented in Table C.8.

RECOMMENDED REMEDIAL ALTERNATIVE

Alternative 2 (SVE as an Interim Action, Bioventing in Source Area, Natural Attenuation, Long-Term Monitoring, and Land and Groundwater Use Controls) was recommended for remediation of Site ST-27 based on its expected effectiveness in stabilizing the dissolved plume and attaining Tier 2 SSTLs, its relative simplicity with respect to technical and administrative implementation, and its relatively low overall cost.

The conservative analytical model results suggest that the implementation of bioventing after SVE in the source area could reduce the total mass of contaminants that could be introduced into the groundwater over time at Site ST-27. There is considerable evidence that SVE followed by *in situ* bioventing will effectively reduce fuel-related contamination in soils and in soil gas in the vicinity of the source area at Site ST-27. Most importantly, SVE will immediately reduce potentially explosive or hazardous concentrations of fuel vapors from shallow subsurface soils.

Given the current and projected industrial land use at Site ST-27 and in surrounding areas, no active groundwater remediation is required at this site to protect human health or the environment (i.e., there is not a completed exposure pathway at the site). Conservative modeling predicted limited soil gas volatilization into indoor and outdoor air under natural convective/diffusive processes and limited downgradient plume migration, with no off-base migration. Long-term groundwater monitoring will be used to verify the effectiveness of natural attenuation and to assure that COPCs do not migrate beyond the area under reliable exposure controls. Once plume stability has

been verified by several years of monitoring, the site will qualify for the SCDHEC Mixing Rule Exemption.

Regulatory Approval

In June of 1997 SCDHEC responded with a written request for additional information and/or clarification of several points, but agreed with the remediation strategy presented in the CAP. A final version of the CAP was provided to the Air Force and SCDHEC in August of 1997.

Remedial Action Implementation and Long-Term Monitoring

The SVE system operated for approximately 170 days between February 1996 and May 1997 (this includes the 64 day pilot test period). Once TVH soil gas concentrations were reduced to acceptable levels, the SVE system was converted to an air injection bioventing system. At the start of the pilot test, the concentration of total volatile hydrocarbons (TVH) of influent gas into the SVE system was greater than 20,000 ppmv. Concentrations had been reduced to 740 ppmv at the time the system was permanently shut down. Based on an average flow rate of 17.3 scfm and an average TVH influent concentration of 2,560 ppmv, an estimated 3,030 pounds of volatile hydrocarbons were removed during SVE operations. The internal combustion engine used to destroy the volatile hydrocarbons operated at an average 97 percent efficiency.

At the conclusion of approximately 2 years of bioventing operations, compliance soil samples will be collected to determine the degree of contaminant reduction. If contaminant levels have been reduced to acceptable levels (i.e., below the Tier 2 soil leaching SSTLs), the bioventing system will be deactivated. Based on results from the pilot tests performed at Site ST-27, 2 years should be adequate to reduce COPC concentrations in contaminated soils at Site ST-27 to below Tier 2 soil leaching SSTLs. Seasonal groundwater elevation changes of 2-3 feet are common at this site. During the dry season, the fuel residuals in the capillary fringe will be "dewatered" and available for bioventing of COPCs.

Long-term groundwater monitoring is being proposed to verify that engineered source reduction technologies and natural chemical attenuation processes are sufficient to achieve the desired degree of remediation. Careful implementation of the long-term groundwater monitoring plan is a key component of this CAP. The proposed remedial alternative for this site calls for groundwater sampling every year until SSTLs are attained at every sampling location. Additionally, 2 years of verification sampling will be performed after SSTLs are attained to confirm plume stability and qualify the site for the SCDHEC Ground-Water Mixing Rule Exemption.

A total of 10 wells (5 wells within the plume and 5 point of action wells outside of the plume) will be used to monitor the stability of the dissolved COPC plume at the site over time. The purpose of the monitoring events are to confirm that natural chemical attenuation processes are reducing COPC concentrations and limiting mobility. These wells are located within and surrounding the characterized areal extent of the dissolved COPC plume to ensure that implemented remedial actions and natural chemical

attenuation processes are sufficient to eventually attain the most restrictive SSTLs and ensure plume containment.

Verification of Land and Groundwater Use Controls

An important element of the recommended corrective action at Site ST-27 is land and groundwater use controls. On the basis of the exposure pathways analysis, Site ST-27 is and will continue to be acceptable for continued industrial use provided nonintrusive workers do not come into direct contact with impacted media on a regular basis, and intrusive workers do not engage in excavation activities that disrupt the concrete apron near the source area without appropriate personal protective equipment. It is recommended that access to the site continue to be restricted. This action will prohibit unauthorized site access and unplanned ground disturbance.

The target cleanup objectives also are based on the assumption that future land use will not require extraction of shallow site groundwater for potable uses. Any future lease or new land use of this land must stipulate that shallow groundwater will not be extracted within 1,000 feet of detected dissolved contamination until COPC concentrations have been reduced below applicable concentrations.

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TABLE C.1
IMPACT OF SVE PILOT TEST ON SOIL GAS CHEMISTRY
CORRECTIVE ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
SITE ST-27, CHARLESTON AFB, SOUTH CAROLINA

Vapor Monitoring Point	Distance From HVW (feet)	Initial Values (2/7/96)				Day 34 of Testing (3/12/96)			
		TVH (ppmv) ^{a/}	Oxygen (%)	Carbon Dioxide (%)	Vacuum (inches water)	TVH (ppmv)	Oxygen (%)	Carbon Dioxide (%)	Vacuum (inches water)
MP-1	85	>20,000 ^{b/}	3.7	3	0	5,000	8.5	4.8	0.1
MP-2	65	>20,000 ^{b/}	1.8	3.9	0	10,000	10.4	4.1	0.2
MP-3	50	66,000	0	8	0	5,000	0	8.8	0.1
MP-4	10	200,000	0	5.5	0	6,200	15.5	3.9	5.5
MP-5	45	110,000	0	4.5	0	5,200	2.2	8.9	0.3
MP-6	25	>20,000 ^{b/}	0.6	4.3	0	18,400	2.2	6.0	3.9
MP-7	115	>20,000 ^{b/}	0.6	4.3	0	1,480	0	7.2	0
MP-8	75	>20,000 ^{b/}	0	5.9	0	6,800	0.2	6.9	0
MPA	40	120,000 ^{c/}	0 ^{c/}	6.9 ^{c/}	0	8,600	1.8	6.5	0.5
MPB	30	>20,000 ^{b/}	0 ^{c/}	NA ^{d/}	0	11,800	1.8	6.7	0.6
MPC	20	75,000 ^{c/}	0	6.0	0	10,200	1.1	6.8	0.9

^{a/} TVH = Total volatile hydrocarbons; ppmv = parts per million volume per volume.

^{b/} TVH concentrations above calibration limit of field instrument (Gas Tech TraceTechor™).

^{c/} Based on ES (1993) bioventing pilot test analytical results.

^{d/} NA = Not available.

TABLE C.2
TIER 1 EVALUATION
COMPARISON OF SITE SOIL CONCENTRATIONS TO DIRECT-CONTACT RBSLs
SITE ST-27 CORRECTIVE ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
CHARLESTON AFB, SOUTH CAROLINA

Detected Analytes	Detected Site Maximum Concentration	SCDHEC Commercial RBSL ^{a/}	Max. Conc.	USEPA Industrial RBSL	Max. Conc.	Units
			Exceeds Commercial RBSL		Exceeds Industrial RBSL	
Benzene	34	99	No	200	No	mg/kg
Toluene	320	200000	No	410000	No	mg/kg
Ethylbenzene	150	100000	No	200000	No	mg/kg
Xylenes (Total)	620	1000000	No	1000000	No	mg/kg
Naphthalene	48	41000	No	82000	No	mg/kg
Benzo(a)anthracene	0.26	3.9	No	7.8	No	mg/kg
Benzo(b)fluoranthene	0.056	3.9	No	7.8	No	mg/kg
Benzo(k)fluoranthene	0.026	39	No	78	No	mg/kg
Chrysene	0.064	390	No	780	No	mg/kg
Acenaphthene	1.5	- ^{b/}	-	120000	No	mg/kg
Anthracene	0.38	-	-	610000	No	mg/kg
Benzo(a)pyrene	0.036	-	-	0.78	No	mg/kg
bis(2-Ethylhexyl)phthalate	26	-	-	410	No	mg/kg
Chlorobenzene	21	-	-	41000	No	mg/kg
Fluoranthene	0.65	-	-	82000	No	mg/kg
Fluorene	2.3	-	-	82000	No	mg/kg
Pyrene	0.67	-	-	61000	No	mg/kg
1,2,4-Trimethylbenzene	360	-	-	100000	No	mg/kg
1,3,5-Trimethylbenzene	162	-	-	100000	No	mg/kg
2-Methylnaphthalene	67	-	-	-	-	mg/kg
Phenanthrene	2	-	-	-	-	mg/kg
1,2,3,4-Tetramethylbenzene	160	-	-	-	-	mg/kg
1,2,3-Trimethylbenzene	185	-	-	-	-	mg/kg

Sources: SCDHEC, 1995; USEPA Region III, 1996.

^{a/}RBSL = risk-based screening level.

USEPA Region III (1995) criterion.

^{b/}"-" = value not available.

TABLE C.3
TIER 1 EVALUATION
COMPARISON OF SITE SOIL CONCENTRATIONS TO SOIL LEACHABILITY RBSLs
SITE ST-27 CORRECTIVE ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
CHARLESTON AFB, SOUTH CAROLINA

Detected Analytes	Average Site Concentration	SCDHEC Leachability RBSL ^{a/}	Avg. Conc.	USEPA Leachability RBSL	Avg. Conc.	Units
			Exceeds SCDHEC RBSL		Exceeds USEPA RBSL	
Benzene ^{b/}	3.62	0.007	Yes	0.016	Yes	mg/kg
Toluene ^{b/}	37.7	1.7	Yes	4	Yes	mg/kg
Ethylbenzene ^{b/}	38.2	1.5	Yes	4	Yes	mg/kg
Xylenes (Total) ^{b/}	148	44	Yes	59.2	Yes	mg/kg
Naphthalene ^{b/}	11.8	0.2	Yes	24	No	mg/kg
Benzo(a)anthracene	0.171	0.7	No	0.56	No	mg/kg
Benzo(b)fluoranthene	0.056	0.66	No	3.2	No	mg/kg
Benzo(k)fluoranthene	0.026	4.6	No	3.2	No	mg/kg
Chrysene	0.064	0.66	No	0.8	No	mg/kg
Acenaphthene	0.726	- ^{c/}	-	160	No	mg/kg
Anthracene	0.188	-	-	3440	No	mg/kg
Benzo(a)pyrene	0.036	-	-	3.2	No	mg/kg
bis(2-Ethylhexyl)phthalate	5.07	-	-	8.8	No	mg/kg
Chlorobenzene ^{b/}	3.05	-	-	0.48	Yes	mg/kg
Fluoranthene	0.441	-	-	784	No	mg/kg
Fluorene	0.664	-	-	128	No	mg/kg
Pyrene	0.443	-	-	1120	No	mg/kg
1,3,5-Trimethylbenzene ^{b/}	47.4	-	-	0.208	Yes	mg/kg
2-Methylnaphthalene	16.1	-	-	-	-	mg/kg
Phenanthrene	0.604	-	-	-	-	mg/kg
1,2,3,4-Tetramethylbenzene	38.3	-	-	-	-	mg/kg
1,2,3-Trimethylbenzene	50.7	-	-	-	-	mg/kg
1,2,4-Trimethylbenzene	117	-	-	-	-	mg/kg

Sources: SCDHEC, 1995; USEPA Region III, 1995.

^{a/}RBSL = risk-based screening level.

^{b/}Analyte was retained for further evaluation if site concentration exceeds either SCDHEC (1995) or USEPA Region III (1996) criterion.

^{c/}"-" = value not available.

TABLE C.4
TIER 1 EVALUATION
COMPARISON OF SITE GROUNDWATER CONCENTRATIONS TO RBSLs
SITE ST-27 CORRECTIVE ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
CHARLESTON AFB, SOUTH CAROLINA

Detected Analytes	Detected Site Maximum Concentration	SCDHEC RBSL ^{a/}	Max. Conc.		Units
			Exceeds SCDHEC RBSL	Exceeds USEPA RBSL	
Benzene ^{b/}	6900	5	Yes	0.36	µg/L
Toluene ^{b/}	10000	1000	Yes	750	µg/L
Ethylbenzene ^{b/}	2400	700	Yes	1300	µg/L
Xylenes (Total)	6100	10000	No	12000	µg/L
Naphthalene ^{b/}	270	25	Yes	1500	µg/L
Acenaphthene	1	- ^{c/}	-	2200	µg/L
Acetone	220	-	No	3,700	µg/L
Chlorobenzene ^{b/}	41	-	-	39	µg/L
1,1-Dichloroethane	1.4	-	-	810	µg/L
cis-1,2-Dichloroethene	26	-	-	61	µg/L
Diethylphthalate	9	-	-	29000	µg/L
2,4-Dimethylphenol	61	-	-	730	µg/L
Di-n-butylphthalate	1	-	-	3700	µg/L
Methylene Chloride	1	-	-	4.1	µg/L
2-Methylphenol(o-Cresol)	32	-	-	1800	µg/L
4-Methylphenol(p-Cresol)	45	-	-	180	µg/L
Phenol	5	-	-	22000	µg/L
Trichloroethene	0.8	-	-	1.6	µg/L
1,1,1-Trichloroethane	4	-	-	1300	µg/L
1,2,4-Trimethylbenzene ^{b/}	1400	-	-	300	µg/L
1,3,5-Trimethylbenzene ^{b/}	390	-	-	300	µg/L
2-Methylnaphthalene	120	-	-	-	µg/L
Phenanthrene	1	-	-	-	µg/L
1,2,3,4-Tetramethylbenzene	140	-	-	-	µg/L
1,2,3-Trimethylbenzene	400	-	-	-	µg/L

Sources: SCDHEC, 1995; USEPA Region III, 1995.

^{a/}RBSL = risk-based screening level.

^{b/}Analyte was retained for further evaluation if site concentration exceeds either SCDHEC (1995) or USEPA Region III (1996) criterion.

^{c/}"-" = value not available.

TABLE C.5
TIER 1 EVALUATION
COMPARISON OF SITE SOIL GAS CONCENTRATIONS TO INHALATION RBSLs
SITE ST-27 CORRECTIVE ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
CHARLESTON AFB, SOUTH CAROLINA

Detected Analytes	Detected Site	SCDHEC	Max. Conc.	USEPA	Max. Conc.	Units
	Maximum Concentration in Soil Gas	RBSL ^{a/} For Ambient Air	Exceeds SCDHEC RBSL	RBSL For Ambient Air	Exceeds USEPA RBSL	
Benzene ^{b/}	2,100,000	0.22	Yes	0.22	Yes	µg/m ³
Toluene ^{b/}	3,000,000	420	Yes	420	Yes	µg/m ³
Ethylbenzene ^{b/}	1,200,000	1,000	Yes	1,000	Yes	µg/m ³
Xylenes (Total) ^{b/}	4,100,000	730	Yes	7,300	Yes	µg/m ³

Sources: SCDHEC, 1995; USEPA Region III, 1995.

^{a/}RBSL = risk-based screening level.

^{b/}Analyte was retained for further evaluation if site concentration exceeds either SCDHEC (1995) or USEPA Region III (1996) criterion.

TABLE C.6
COMPARISON OF ANALYTICAL SOIL DATA TO SOIL LEACHING SSTLs
SITE ST-27 CORRECTIVE ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
CHARLESTON AFB, SOUTH CAROLINA

Soil COPC	Units	Maximum Detected Concentration ^w	Calculated Average Concentration ^{lv}	Soil Leaching SSTL to Prevent Plume Expansion ^d	Soil Leaching SSTL to Attain RME Health-Based SSTL ^{d'}	Soil Leaching SSTL to Attain CT Health-Based SSTL ^{d'}	Does Max. Conc. Exceed Most Stringent SSTL?	Does Avg. Conc. Exceed Most Stringent SSTL?
Benzene	mg/kg	34	3.62	21.9	1.2	3.1	YES	YES
Toluene	mg/kg	320	37.7	198.0	268.3	355.3	YES	NO
Ethylbenzene	mg/kg	150	38.2	97.2	157.7	208.8	YES	NO
Total Xylenes	mg/kg	620	148	393.2	-	-	YES	NO
Naphthalene	mg/kg	48	11.8	305.5	4.4	58.8	YES	YES
Chlorobenzene	mg/kg	21	3.05	13.6	164.4	218.0	YES	NO
1,3,5-Trimethylbenzene	mg/kg	162	47.4	95.2	269.6	357.2	YES	NO

NOTE: Derivation of SSTLs presented in Appendix E as part of chemical fate assessment.

^w Maximum concentrations were obtained from the 1995 sampling event.

^{lv} Average soil concentration were calculated from analytical data collected during the 1995 sampling event.

^d Site-specific soil leaching SSTL based on partitioning relationship developed in Section 6 to evaluate long-term leaching of soil COPC mass from soils. Based on literature-reported K_D value, site-specific foc of 0.005, and simple equilibrium partitioning model used to simulate observed site conditions. Target groundwater concentration to prevent expansion of plume boundary was estimated using analytical model ONED3 (Section 6.6.4). Used target groundwater concentration to "back calculate" groundwater protective SSTL.

^{d'} Site-specific soil leaching SSTL based on partitioning relationship developed in Section 6 to evaluate long-term leaching of soil COPC mass from soils. Based on literature-reported K_D value, site-specific foc of 0.005, and simple equilibrium partitioning model used to simulate observed site conditions. Target groundwater concentration = RME health-based groundwater SSTL (worker dermal exposure to groundwater) was used to "back calculate" groundwater protective SSTL.

^{d'} Site-specific soil leaching SSTL based on partitioning relationship developed in Section 6 to evaluate long-term leaching of soil COPC mass from soils. Based on literature-reported K_D value, site-specific foc of 0.005, and simple equilibrium partitioning model used to simulate observed site conditions. Target groundwater concentration = CT health-based groundwater SSTL (worker dermal exposure to groundwater) was used to "back calculate" groundwater protective SSTL.

TABLE C.7
COMPARISON OF ANALYTICAL GROUNDWATER DATA TO SITE-SPECIFIC TARGET LEVELS
SITE ST-27 CORRECTIVE ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
CHARLESTON AFB, SOUTH CAROLINA

COPC	Units	Detected Site Maximum Concentration ^{a/}	Tier 2 RME Health-Based SSTLs ^{b/}	Tier 2 CT (Average) Exposure Health- Based SSTLs ^{c/}	Tier 1 SCDHEC/EPA Generic RBSLs ^{d/}	Does Detected Site Maximum Concentration Exceed RME SSTL?	If "YES," Does Detected Site Maximum Concentration Exceed CT SSTL?
Benzene	µg/L	6900	240 ^{b/}	640 ^{c/}	0.36	YES	YES
Ethylbenzene	µg/L	2400	2,500	3,400	700	NO	-
Toluene	µg/L	10000	8,800	12,000	750	YES	NO
Naphthalene	µg/L	270	260	330	25	YES	NO
Chlorobenzene	µg/L	41	320	430	39	NO	-
1,2,4,-Trimethylbenzene	µg/L	1400	720	950	300	YES	YES
1,3,5-Trimethylbenzene	µg/L	390	720	950	300	NO	-
cis -1,2-Dichloroethene	µg/L	26	2,000	2,600	61	NO	-

NOTE: Derivation of SSTLs presented in Appendix F.

^{a/}Maximum concentrations were obtained from the 1995-96 risk-based investigation sampling events.

^{b/}RME SSTLs are designed to protect onsite intrusive workers from unacceptable exposure due to incidental exposure via dermal contact with dissolved chemicals in groundwater using site-specific exposure assumptions (carcinogenic value for benzene; noncarcinogenic values for all other COPCs).

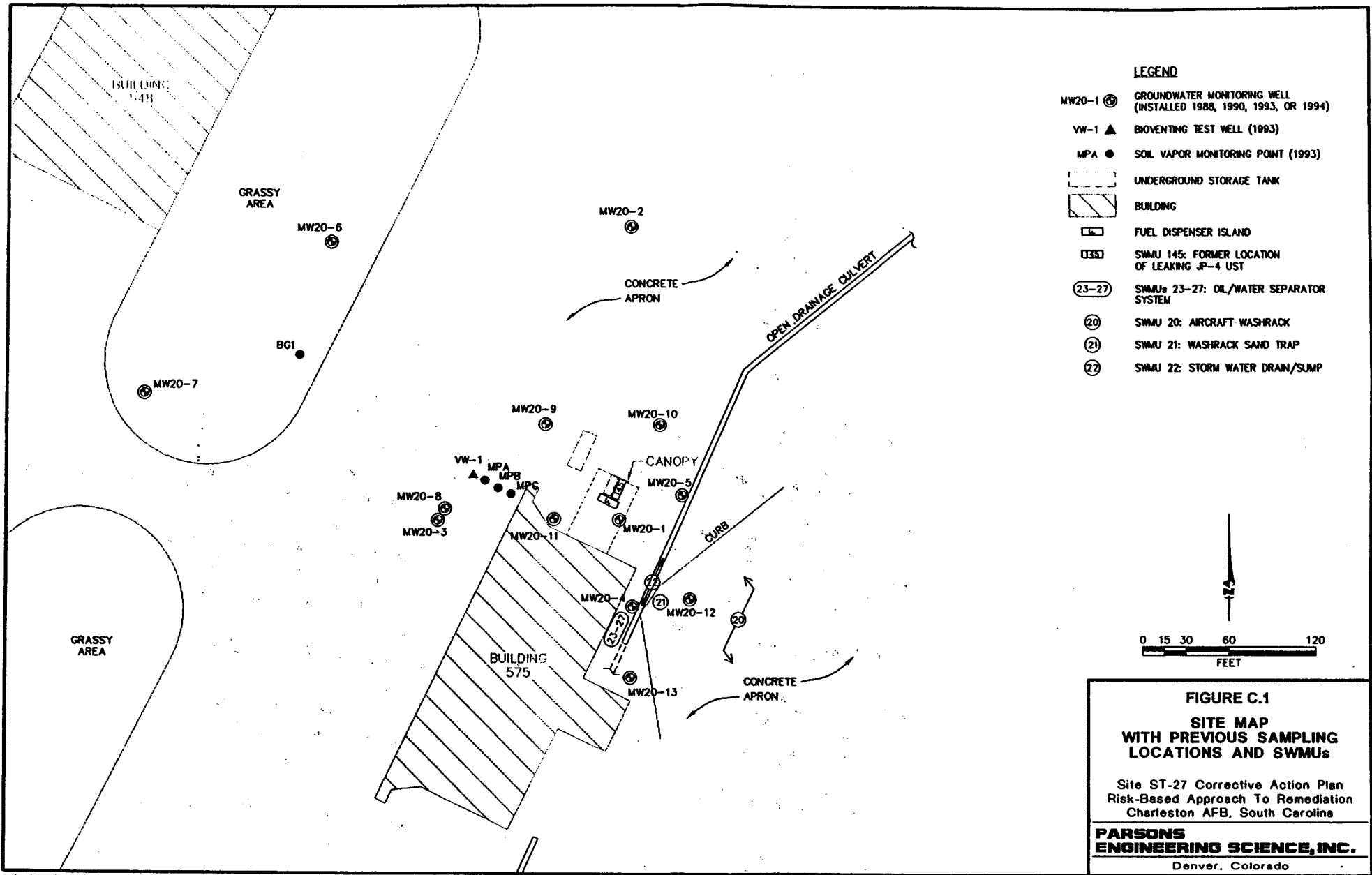
^{c/} Average or CT SSTLs (i.e., SSTLs based on average exposure assumptions) are provided for comparison with RME SSTLs for onsite intrusive workers exposed via incidental dermal contact with dissolved chemicals in groundwater (carcinogenic value for benzene; noncarcinogenic values for all other COPCs).

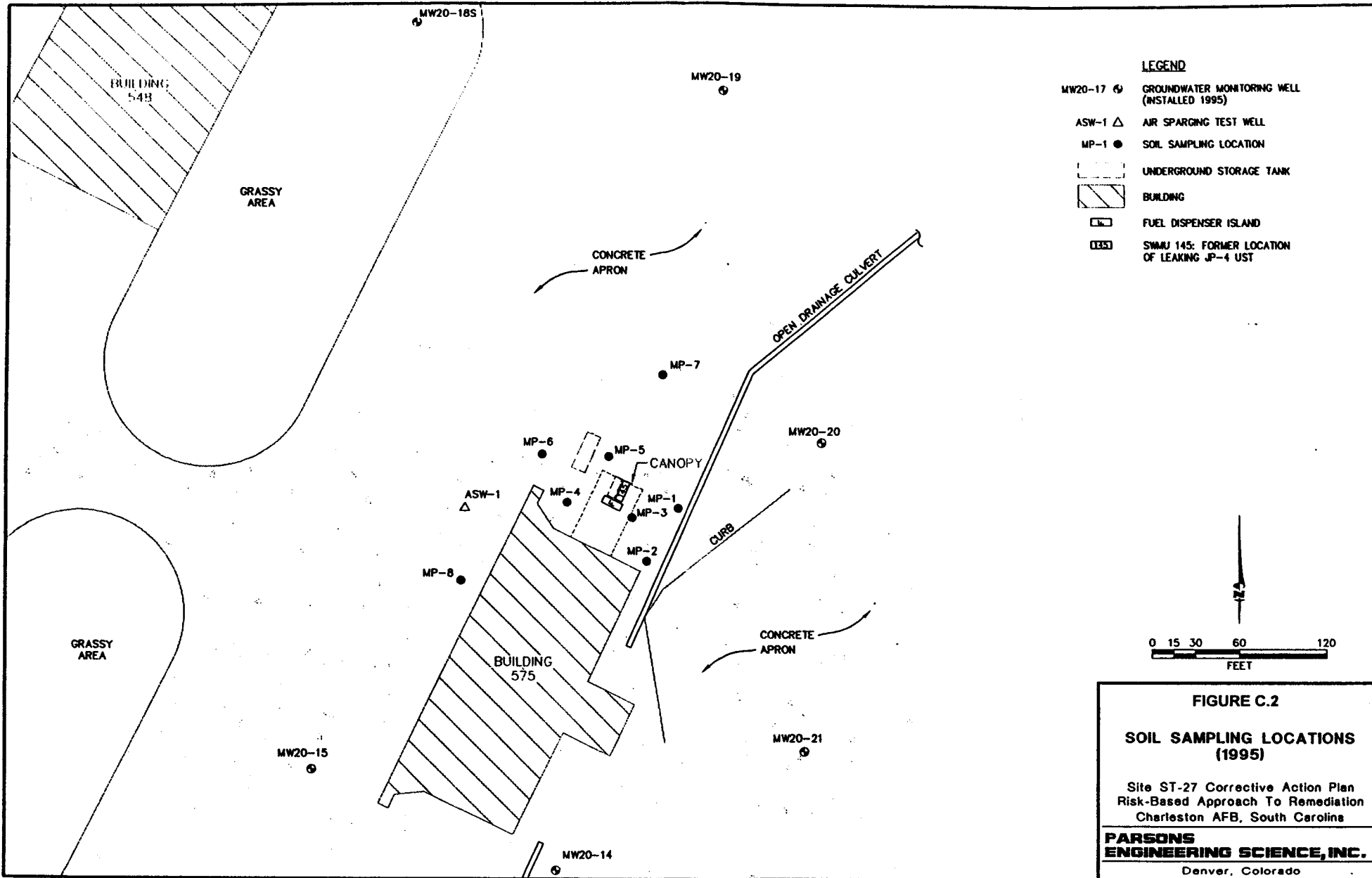
^{d/} SCDHEC (1995)/EPA Region VIII (1996) (the lesser of the two values) generic RBSLs would be protective of onsite workers whose drinking water comes from an onsite groundwater source.

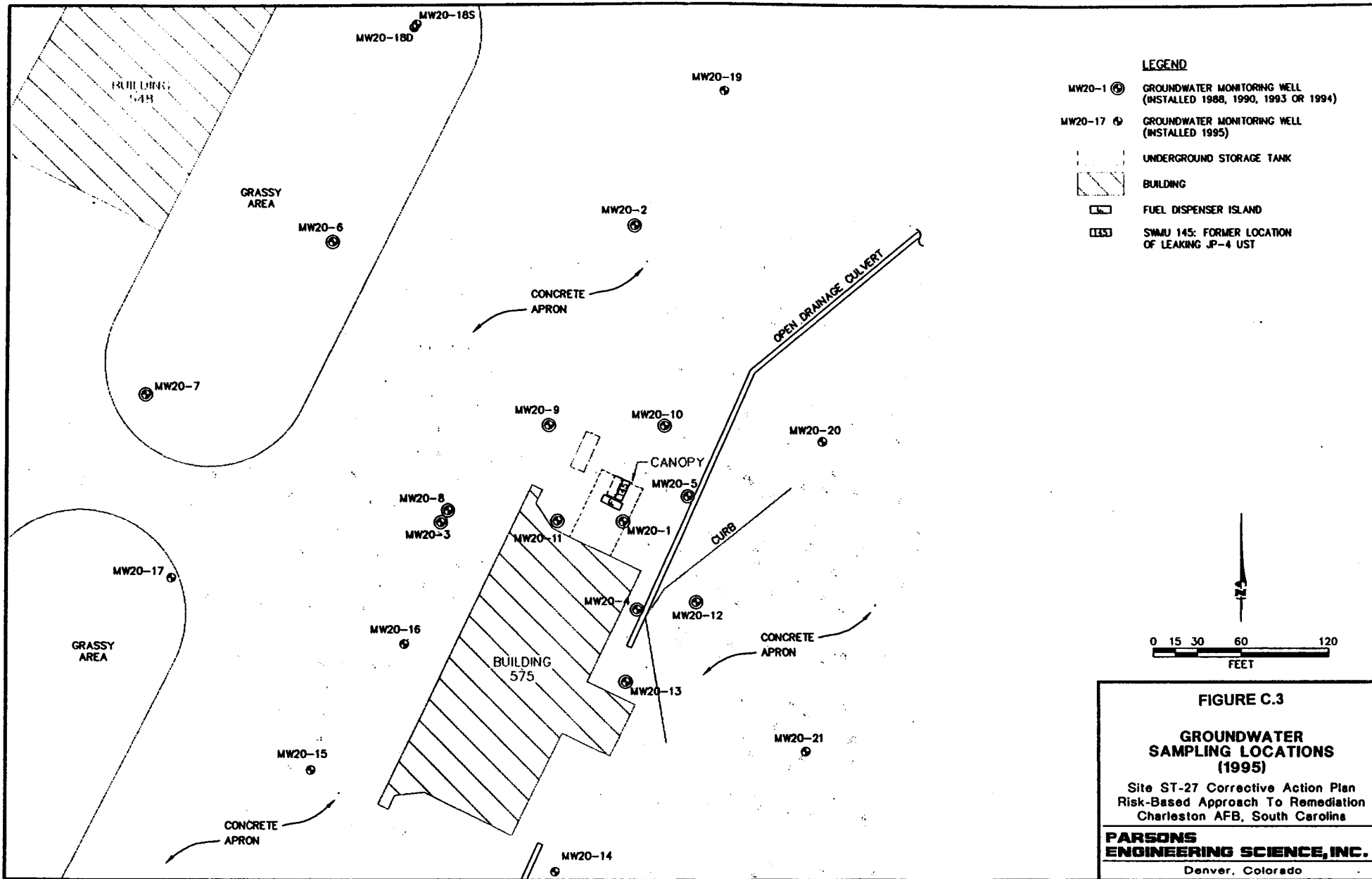
^{e/} Health-based SSTL values for benzene (a carcinogen) are based on target risk levels of 10^{-6} (see Appendix F for calculated SSTLs values based on target risks of 10^{-4} and 10^{-5}).

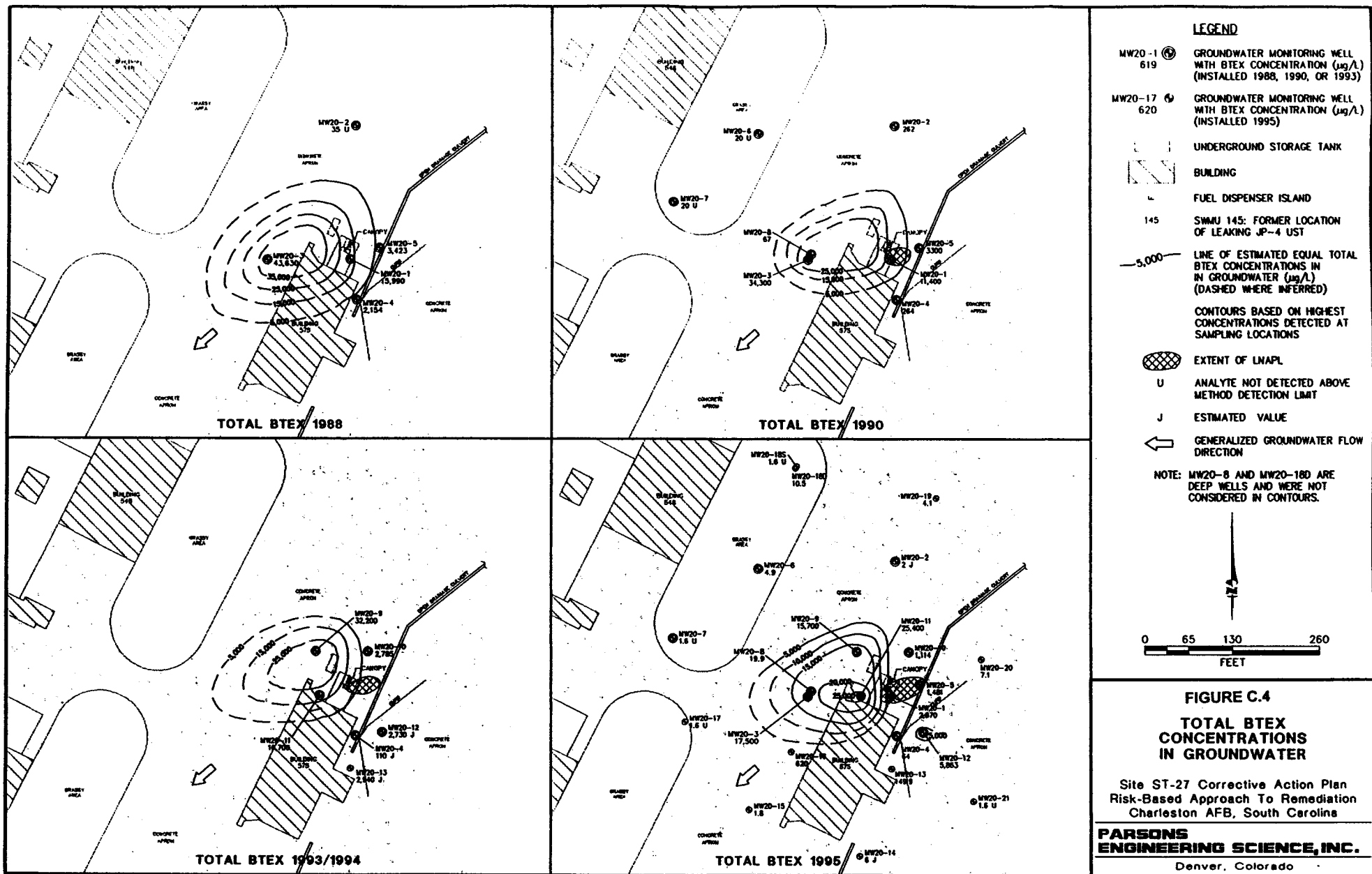
TABLE C.8
SUMMARY OF REMEDIAL ALTERNATIVE EVALUATION
CORRECTIVE ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
SITE ST-27, CHARLESTON AFB, SOUTH CAROLINA

Remedial Alternative	Effectiveness	Implementability	Present Worth Cost Estimate
Alternative 1			\$200,550
-SVE as an Interim Action -Natural Attenuation -Long-Term Monitoring -Land and Groundwater Use Controls	Contaminant mass, volume, and toxicity will gradually be reduced by natural attenuation alone. Most restrictive Tier 2 SSTLs will be met in approximately 20 years.	Technically simple and easy to implement. Long-term groundwater monitoring for 22 years is required. Groundwater use restrictions need to be implemented and would not incur any additional land use restriction beyond those currently in place at Site ST-27. Requires public education.	
Alternative 2			\$202,522
-SVE as an Interim Action - <i>In Situ</i> Bioventing in Source Area -Natural Attenuation -Long-Term Monitoring -Land and Groundwater Use Controls	Similar to Alternative 1, with the addition of bioventing to increase contaminant removal and degradation in the source area. Attainment of the most restrictive Tier 2 SSTLs in approximately 10 years. Pilot testing indicated bioventing will significantly remove BTEX compounds from unsaturated soils.	Long-term groundwater monitoring for 12 years is expected. The bioventing system is expected to operate for 2 years. This system will require weekly monitoring. Groundwater and land use restrictions would be the same as Alternative 1. Positive public perception.	
Alternative 3			\$609,905
-SVE - <i>In Situ</i> Biosparging in Source Area -Natural Attenuation -Long-Term Monitoring -Land and Groundwater Use Controls	Similar to Alternative 2, with biosparging for the active remediation of groundwater contamination. Tier 2 SSTLs will be met in approximately 9 years.	Operation of the biosparging/SVE system for 3 years is expected. Long-term groundwater monitoring for 11 years will be required. Lengthy lead time required for design and installation of groundwater biosparging system. Positive public perception.	









CASE STUDY D
SITE ST-14
CARSWELL AFB/NAS FORT WORTH JRB

INTRODUCTION

Parsons Engineering Science, Inc. (Parsons ES) was retained by the United States (US) Air Force Center for Environmental Excellence (AFCEE) to prepare a remedial action plan (RAP) for the risk-based remediation of soil and groundwater contaminated with fuel hydrocarbons at Site ST14 at Carswell Air Force Base (AFB)/Naval Air Station (NAS) Fort Worth Joint Reserve Base (JRB), in Fort Worth, Texas (the Base). The purpose of the RAP was to develop and describe a recommended remedial action to be implemented at Site ST14 that met the requirements of the State of Texas Natural Resource Conservation Commission (TNRCC). In particular, the remedial action was performed in accordance with Title 31 of the Texas Administrative Code (TAC), Chapter 334, the petroleum storage tank (PST) rules.

As described in the main text of this handbook, risk-based remediation is designed to combine natural physical, chemical, and biological processes with low-cost source reduction technologies such as *in situ* bioventing, as necessary, to economically reduce potential risks to human health and the environment posed by petroleum releases. The RAP was prepared as part of a multi-site initiative sponsored by AFCEE to develop this handbook on how best to implement risk-based corrective actions (RBCAs) at fuel-contaminated sites.

REGULATORY FRAMEWORK

The TNRCC has adopted a tiered, risk-based approach to the remediation of petroleum hydrocarbon contaminated sites that is similar to the American Society for Testing and Materials (ASTM) RBCA process and the Air Force risk-based remediation strategy. This approach allows for the establishment of site-specific target levels (SSTLs) based on an analysis of potential receptor exposures to chemical contamination at or migrating from the release site. Generic cleanup criteria (developed by the TNRCC) and site-specific chemical fate and receptor exposure data are used to identify the most cost-effective remedial approach.

The RAP for Site ST14 combined into a single document the documentation elements specified by the PST Division of TNRCC (TNRCC, 1994a, 1994b, 1995a, 1995b, and 1995c) for a limited site assessment, Plan A (Tier 1) and Plan B (Tier 2) comprehensive assessments, a Plan B exposure assessment, and a proposal for implementing an appropriate remedial action at the site. Plan A, or Tier 1 assessments are designed to establish cleanup levels based on specified methods, conservative assumptions regarding potential human exposure, and a limited number of site-specific factors. Plan A target concentrations have been defined by the TNRCC for both generic unrestricted (i.e., residential) and generic industrial/commercial land use assumptions. Plan A evaluations have been defined by TNRCC (1994a) as screening-level evaluations (i.e., a typical Tier 1 screening using risk-based screening levels (RBSLs) as described in Section 3 of the handbook). As presented in Section 3 of the handbook, some states have developed their own screening criteria, making the development of Tier 1 RBSLs unnecessary. The State of Texas is a good example of where the state regulatory agency has already defined Tier 1 RBSLs, making it very simple to perform a Tier 1 evaluation. Furthermore, TNRCC (1994a) recommends that all sites be initially evaluated under Plan A.

The generic cleanup criteria or RBSLs are used to identify which, if any, contaminants and environmental media may warrant additional evaluation or remediation to protect human health and the environment. If measured site concentrations do not exceed the applicable Plan A criteria, no additional remedial actions will be required by the TNRCC other than maintaining the land use in accordance with the exposure assumptions used to derive the generic cleanup goals. However, in the event that measured concentrations exceed the applicable Plan A target concentrations, a Plan B evaluation may be necessary to establish reasonable SSTLs.

Plan B, or Tier 2, remedial actions are based on the outcome of a limited risk assessment to evaluate current and potential human health risks and short-term and long-term fate of the contaminants at the site. The State of Texas allows alternate, health-protective SSTLs to be proposed as part of a Plan B evaluation. Refer to Section 3.2 of the handbook for further discussion on the development of SSTLs. Although Plan B (i.e., Tier 2) evaluations usually involve more rigorous analysis and may require use of institutional controls or engineered barriers to ensure that exposure conditions do not change over time, they result in a more focused remediation of those contaminants that actually pose a risk to potential receptors. A Plan B evaluation will result in the same level of health protection as a Plan A, because remediation is focused on those elements that pose a risk under given site conditions.

SITE BACKGROUND

Operational History

Site ST14 is located in the East Area of Carswell AFB/NAS Fort Worth JRB. The Base is located approximately 6 miles west of downtown Fort Worth, Texas. Four discrete sites have been identified in the East Area of the Base that may be potential sources of contamination (Radian Corporation [Radian], 1991). These sites include Site LF01 (landfill), Site BSS (Base service station), Site ST14 (POL tank farm and adjacent fuel loading area), and Site SD13 (unnamed stream and abandoned gasoline station). Sites ST14 and SD13 are located in the southern portion of the East Area. Because Site SD13 is downgradient from Site ST14, dissolved contamination originating from the POL tank farm and adjacent fueling areas may have migrated to and impacted this area. The other two East Area sites are located north of (essentially upgradient from) the dissolved plume originating at Site ST14, and data indicate that they are not impacted by contamination originating from Site ST14.

Site ST14 is divided into two areas, Site ST14A and Site ST14B. Site ST14A consists of a fuel loading area and an area downgradient from the fuel loading area. Site ST14B is the tank farm portion of the site and consists of three aboveground storage tanks (ASTs). Three additional tanks, which were formerly located at Site ST14B, have been dismantled. The layout of Site ST14 is shown in Figure D.1. All of Site ST14 has been an area of fuel storage during most of the Base's operating history (i.e., from 1942 to the present).

During the early 1960s, JP-4 jet fuel was discovered in soil and groundwater at and downgradient from Site ST14. Leaking underground fuel lines are the suspected source of subsurface contamination at this site. A french drain system constructed of perforated ceramic tile, and interceptor box, and a pumphouse was apparently installed

downgradient from the site to collect fuel product leaking from Site ST14 and possibly Site SD13. The installation date and construction details of the french drain system are unknown; no as-built drawings were located (Law Environmental Government Services [Law], 1994). In the mid 1960s, the interceptor box and pumphouse were replaced with an oil/water separator. The french drain system was apparently connected to this underground oil/water separator. Water from this oil/water separator was discharged into a perennial unnamed stream, which flows about 200 feet east into Farmers Branch. Farmers Branch in turn discharges to the Trinity River along the eastern boundary of the Base

Previous Investigations

Sites ST14A, ST14B, and SD13 have been characterized under the US Air Force IRP (Radian, 1985, 1988, and 1989). Additional site investigation data were collected at these sites as part of the 1993 bioventing pilot test program sponsored by AFCEE (ES, 1993), the 1994 RFI completed by Law, and the 1994/1995 risk-based investigation conducted by Parsons ES. All available data from these sources were used in the RAP to characterize the nature and extent of contamination and to determine the type, magnitude, and timing of remediation necessary to protect human health and the environment. The following briefly summarizes the site characterization data available prior to 1994.

The results of two soil gas surveys conducted in 1987 (Radian, 1988) and 1993 (ES, 1993) at Site ST14A both indicated a soil gas plume centered in the northern end of the site (Figure D.1). Compound-specific data were collected in this area as part of the 1993 bioventing pilot test. Compound-specific soil gas analytical results indicated that fuel hydrocarbons were the principal contaminants. No chlorinated volatile organic compounds (VOCs) were detected. Soil gas samples collected in 1993 from contaminated soils at Site ST14A had high concentrations of total volatile hydrocarbons (TVH), but relatively low concentrations of specific compounds such as ethylbenzene and xylenes. These soil gas samples also were depleted in gaseous oxygen (ranging from 0.8 to 3.8 percent) and had elevated carbon dioxide, suggesting that significant biological fuel degradation may be occurring in fuel-contaminated soils at the site (ES, 1993).

Although no soil samples were collected at Site ST14B for chemical analysis prior to 1994, soil data were collected at Site ST14A as part of the early IRP investigations (Radian, 1985, 1988, 1989, and 1991) and the bioventing pilot test (ES, 1993). The previous investigations indicated that hydrocarbon fuel contamination in soil at Site ST14A extends from the surface, or near surface, to a depth of approximately 12 feet below ground surface (bgs), but is most concentrated in the 8- to 11-foot bgs interval. Elevated concentrations of total recoverable petroleum hydrocarbon (TRPH) and benzene, toluene, ethylbenzene, and xylene (BTEX) in soil samples were measured throughout Site ST14A.

More than 2 feet of free product was encountered in 1990 at one groundwater monitoring well at Site ST14A. Limited free product (i.e., a thin film) also was encountered in the vent well and several of the vapor monitoring points installed at Site ST14A in 1993 as part of the bioventing pilot test. All of these sampling locations are within 40 feet of the groundwater monitoring well. Base personnel have been

monitoring free product thickness about 1 year. The average product thickness measured in the well from mid-1993 to mid-1994 was 0.75 inch. Product was hand bailed from the well during each measurement event.

Early investigations at Site ST14 suggested the presence of two distinct dissolved hydrocarbon plumes, one originating near Site ST14A and one near ST14B. Several VOCs were detected in the groundwater at Site ST14 during these sampling events, including BTEX and chlorobenzene. Of these VOC contaminants, ethylbenzene was detected most frequently. It is important to note that detected contaminant concentrations in groundwater samples collected in 1990 were lower than the concentrations of the same analytes detected during previous investigations. This trend was a good indicator that natural chemical attenuation processes may be limiting the persistence, concentration, mobility, mass, and toxicity of dissolved contaminants over time.

Surface water quality data also were collected as part of the early IRP investigations to determine whether fuel hydrocarbon contamination from Site ST14 and/or Site SD13 was being intercepted by the subsurface french drain system. Both benzene and toluene were detected in surface water samples collected from the unnamed stream in 1986. Four additional surface water samples were collected as part of the 1990 IRP sampling effort at the unnamed stream. Benzene and toluene were again the most frequently detected VOCs, although the concentrations were significantly less than those measured previously. Concentrations of these contaminants decreased with increasing distance downstream, probably due to photooxidation, volatilization, and dilution. Based on this trend, it appears that any natural groundwater discharge entering the stream at more permeable, downgradient locations does not contribute significant concentrations of contaminants to Farmers Branch or West Fork of the Trinity River. The french drain system and oil/water separator was identified as a probable source of the measurable concentrations of fuel hydrocarbon contamination in surface water.

A baseline risk assessment (BRA) was prepared for both Site ST14 and SD13 using the 1990 IRP analytical data (Radian, 1991) and EPA (1986) risk assessment guidance, which has since been superseded. Although the BRA indicated that both carcinogenic and noncarcinogenic human health risks associated with exposure to measured concentrations of chemical contamination at Site ST14 and SD13 were below levels warranting remedial action, these sites were identified as high-priority sites because they may represent a direct contaminant source or contaminant migration pathway to Farmers Branch and the Trinity River. Additionally, the 1991 report cited significant uncertainty about the processes involved in subsurface contaminant transport and the potential for increased risks over time.

DEFINING SITE CHARACTERIZATION DATA REQUIREMENTS

In order to make a credible and defensible RBCA decision for this site, an adequate and appropriate site characterization data must be available. Sufficient data must be collected to conduct a quantitative fate and transport analysis, perform an exposure pathways analysis and limited risk-assessment, and evaluate the potential treatability of contaminated media using low-cost remedial technologies and approaches. As part of the risk-based investigation at Site ST14, emphasis was placed on filling data gaps

identified during previous investigations and on collecting data relevant to documenting the *in situ* biodegradation of fuel hydrocarbons in soil and groundwater.

After a review of previously collected site data, data gaps and target analytes were identified. Data gaps were determined by reviewing a preliminary conceptual site model (CSM) (Section 4 of the handbook) to identify previously undefined potential contaminant migration pathways. Target analytes were identified based on the chemical constituents of the suspected sources (i.e., releases of jet fuel and/or gasoline resulting from spills or leaks associated with the fuel yard, fuel storage area, and the abandoned gas station), and the results of previous sampling activities at the site. It was determined that additional soil gas, soil gas flux, subsurface soil, groundwater, and surface water samples were required to adequately quantify potential contaminant migration pathways and associated risk at Site ST14. Surface water stream flow velocities and hydraulic conductivity tests were also performed at the site to quantify the velocity and transport potential of surface water and groundwater. Source reduction technology pilot testing, present and future land use, and groundwater use data also were required for the site to facilitate risk-based Plan A screening, Plan B evaluation, and final remedial design.

Based on the chemical composition of JP-4 jet fuel and gasoline, BTEX, chlorobenzene, and the polynuclear aromatic hydrocarbons (PAHs) were identified at the target analytes for all media at Site ST14. Analytical data on trichloroethene (TCE) also were collected at several locations to verify that upgradient groundwater contamination had not migrated to and impacted Site ST14. Electron acceptor and other groundwater geochemical data also were collected to facilitate an evaluation of the potential for natural chemical attenuation of dissolved hydrocarbon contamination.

SITE INVESTIGATION

A field investigation was conducted by Parsons ES at Site ST14 during 1994 and 1995. The following sampling and testing activities were performed by Parsons ES at the site:

- Collection of analytical soil gas samples at eight locations;
- Collection and analytical analysis of soil gas flux samples at seven locations;
- Drilling and installation of 27 new permanent groundwater monitoring wells, 17 bioventing wells, two soil boreholes, one biosparging pilot test well, and two vapor monitoring points;
- Collection of 59 subsurface soil samples for analytical analysis from 42 new soil boreholes drilled for completion of monitoring wells, vent wells, or vapor monitoring points (samples were not collected from 7 of the 49 soil borings);
- Collection of seven surface water samples from five locations for analytical testing to evaluate surface water quality of the unnamed stream and Farmers Branch. Five samples were collected under low-flow conditions in August 1994, and two additional samples were collected following a heavy rainfall event in April 1995 to assess relative contaminant contribution to the unnamed stream;

- Measurement of stream flows under low and normal flow conditions to evaluate the portion of flow contributed from the unnamed stream to Farmers Branch;
- Collection of 21 groundwater samples from temporary Hydropunch® sampling locations for analytical and field testing (part of 1994 RFI effort);
- Collection of 27 groundwater samples from new monitoring wells for analytical laboratory and field testing;
- Collection of 16 groundwater samples from previously existing monitoring wells for analytical laboratory and field testing;
- Performance of a bioventing and biosparging pilot test; and
- Performance of aquifer slug tests and conductivity tracer tests to provide further information on the hydrogeologic conditions of the shallow aquifer beneath the East Area sites.

Because there are such a large amount of sampling locations associated with Site ST14 it is not possible to effectively present figures of the sampling locations in this brief case study. Table D.1 presents the fixed-base analytical and field methods used for the analysis of soil gas, soil, and water (ground and surface) samples collected at the site.

Source Reduction Technology Testing

Two potential source reduction technologies, biosparging and bioventing, were evaluated during the investigation of fuel related contamination at Site ST14. A single biosparging test well was constructed at Site ST14A to measure the increase in dissolved oxygen (DO) concentrations created in groundwater by sparging, and to determine the flow rates required for a full-scale biosparging system in the event that this type of remediation was warranted. Although the test successfully demonstrated that DO could be increased in the vicinity of the biosparging well, channeling in the subsurface yielded an inconsistent radius of oxygen influence. It was determined that pulsed injection could reduce the effect of channeling at the site.

A bioventing test was performed at Site ST14A as part of a separate AFCEE initiative in 1993. Pilot test results indicated that low rate air injection is an effective method of stimulating aerobic fuel biodegradation and BTEX reduction in Site ST14A soils. The effective radius of oxygen influence for air injection bioventing exceeded 45 feet from each air injection well. For full-scale design a radius of influence of 45 feet was recommended, and vent wells (VWs) installed during the 1994/1995 risk-based investigation were spaced based on this radius. A design air flow rate of 15 actual cubic feet per minute per VW was recommended to effectively oxygenate the desired treatment area while minimizing volatilization.

Present and Future Land Use Information

During the field investigation at the Base, current and future land use information was collected to determine which generic, land-use based, Plan A screening criteria

(RBSL) would be appropriate for the site. Site ST14 has been maintained as an active fuel servicing and storage facility for flight operations at Carswell field. The Base was placed on the 1991 Defense Base Closure and Realignment Commission's list for closure. The Base was officially closed on September 30, 1993. However, in 1993, the Commission recommended realignment of several military reserve and guard units to Carswell, such that portions of Carswell are retained by the DOD, as required to support long-term operations associated with the realigning military units. As part of the proposed land reuse plan, several DOD organizations (Navy Reserve, Marine Reserve, Army Reserve/Guard, and Air National Guard units) are being realigned from NAS Dallas, NAS Memphis, and NAS Glenview to Carswell. The Air Force is required to make a series of interrelated decisions concerning the disposition of Base property determined to be in excess of the needs of the DOD. The US Navy, the US Department of Justice, and the Federal Bureau of Prisons (FBOP) are assisting the Air Force in making decisions regarding Carswell property. The US Navy has assumed command of the Base, and FBOP operates a minimum-security prison in the former Base hospital (renovated for use as a detention facility).

An EIS was prepared by the US Air Force to provide information on the potential environmental impacts resulting from proposed reuse of Base property in response to realignment actions. Based on the proposed land reuse plan, Sites ST14A and ST14B will be maintained for Base fueling operations (military). Site SD13 is designated to be part of an open space area associated with the flood-prone areas along Farmers Branch. A small area to the south of Site SD13 will be used as a residential area, although no new building construction is planned. The Base realignment is scheduled to be completed in 1998. The proposed land uses mean that industrial criteria are appropriate for Site ST14.

Groundwater and Surface Water Use Information

Surface water is the main source of drinking water in the vicinity of Carswell AFB/NAS Fort Worth JRB. The City of Fort Worth Water Department is the primary supplier of potable water to the areas surrounding and including the Base. The city obtains its potable water supply from the West Fork of the Trinity River. Nonpotable water from Farmers Branch is used to irrigate the on-Base golf course. Local municipalities obtain water from 21 groundwater wells, respectively; however, no wells were identified within a 0.5-mile radius of Sites ST14 and SD13. The availability of surface water to supply the Base and the surrounding communities was determined to be adequate to maintain military operations and land reuse activities following closure and realignment. Thus, drilling additional potable supply wells at the Base will not be necessary. This is important because it means that as long as groundwater does not impact surface water or migrate more than 0.5 mile from the site, industrial screening criteria will be applicable for Site ST14.

PLAN A SCREENING EVALUATION

After sufficient analytical data and other relevant site information were collected, a Plan A (i.e., Tier 1) screening evaluation was performed for Sites ST14 and SD13 to identify chemicals of potential concern (COPCs) that could require further evaluation. Only those chemicals with site concentrations that exceeded the applicable Plan A target concentrations were considered when establishing the risk-reduction

requirements for the site. However, pursuant to TNRCC (1994a) guidance, the Plan B limited risk assessment accounted for the cumulative effect of all measured organic chemicals, not just the COPCs.

According to the realignment land use plan for the Base, the expected future use of Site ST14 will be industrial (i.e., the site will continue to be used as a fuel storage and supply facility). Based on this proposed future land use, the generic Plan A industrial/commercial criteria were found to be appropriate for the site. Table D.2 compares the maximum analytical concentrations for every compound measured in soil and groundwater at Sites ST14 and SD13 to the Plan A target concentrations for the industrial/commercial land use scenario. If the maximum measured site concentration did not exceed the Plan A target concentration, the compound was not identified as a COPC. If the maximum measured site concentration exceeded the Plan A target concentration, the compound was identified as a COPC.

In addition to protection of human health, the need for environmental protection must be considered when identifying COPCs. Generally, protection of surface water and groundwater will be of primary concern (TNRCC, 1994a). The target remedial objective for surface water is to prevent the discharge of any concentration of fuel hydrocarbon into the water body. However, Plan A target concentrations for surface water are based on the Texas Surface Water Quality Standards of Title 30 TAC, Chapter 307 and 319. Freshwater acute and freshwater chronic surface water quality criteria have been defined. These target concentrations for surface water are used to identify any compounds present in groundwater or surface water at concentrations that could cause unacceptable environmental impacts if an exposure pathway involving surface water is or could be completed at the site. Table D.3 compares the maximum measured groundwater and surface water concentrations to the Plan A environmental protection target concentrations for surface water. Compounds were identified as COPCs for environmental protection concerns if the maximum concentration exceeded the Plan A target concentration for surface water or the health-based Plan A target concentration for groundwater.

Identified Fuel-Related Chemicals of Potential Concern

Compounds shaded in Tables D.2 and D.3 exceed the Plan A industrial/commercial criteria at Site ST14. No concentrations of fuel hydrocarbon chemicals measured in surface water exceeded Plan A environmental protection target concentrations for surface water, although several fuel hydrocarbon compounds measured in groundwater exceeded these surface water criteria. Benzene and hexachlorobenzene are the only compounds identified as fuel-related soil COPCs. No PAH compound was measured at concentrations above the Plan A target concentrations for soil.

Benzene was the only fuel-related compound to be identified as a groundwater COPC. Although bromodichloromethane and methylene chloride were detected in isolated samples at concentrations just slightly above the Plan A target concentration, these compounds are common laboratory contaminants and/or were detected repeatedly in method blanks. Therefore, these compounds were not considered fuel-related COPCs.

The two fuel-related COPCs, benzene and hexachlorobenzene, were considered in detail in the RAP. Organic compounds measured at the site at concentrations that did not exceed the most stringent Plan A target concentrations were considered cumulatively with COPCs in the Plan B limited risk assessment, but did not receive detailed assessment as part of the nature and extent and chemical fate discussions. Emphasis has been given to defining the nature and extent of fuel-related contamination that must be addressed to protect human health and the environment in accordance with the intent of the TNRCC (1994a) risk-based corrective action guidance. Only compounds that may pose a health threat (i.e., a carcinogenic and/or noncarcinogenic risk) to potential receptors or are relevant to conducting remedial technology assessments were considered as part of this risk-based approach to remediation.

PLAN B LIMITED RISK ASSESSMENT

A Plan B limited risk assessment was prepared to quantitatively evaluate potential site risks based on site-specific assumptions regarding potential human exposure and short- and long-term fate of benzene and hexachlorobenzene at Site ST14 and downgradient at Site SD13 (TNRCC, 1994a). A Plan B evaluation was necessary to demonstrate that no imminent threat to human health or the environment exists even though site-related COPCs are present above TNRCC-specified Plan A target concentrations. The Plan B limited risk assessment took into account cumulative exposure to all detected organic chemicals and the short- and long-term fate of the COPCs, as predicted by quantitative modeling results.

Exposure Pathways Analysis

The first step in the Plan B limited risk assessment was an exposure pathways analysis. This analysis examined the potential migration paths a contaminant could take from source to receptor. A completed exposure pathway must consist of a source, a release mechanism, a transport medium, a potential human or ecological receptor, a potential exposure point, and a route of exposure. Each of these elements must be present before a particular exposure pathway can be considered complete. If any one of these elements is missing, the exposure pathway is considered incomplete, and there is no risk. Site-related contamination can present a potential risk to receptors only if exposure pathways are completed.

A site-specific exposure pathways analysis was completed for Site ST14 and Site SD13 to determine the likelihood of human or ecological contact with site-related contamination. The objective of this assessment is to determine which, if any, exposure pathways are complete (USEPA, 1992). Emphasis was given to identifying those pathways where released contaminants may migrate within the environment, but through which potential receptors currently do not come into contact with these chemicals and are not likely to do so in the future. These incomplete exposure pathways were eliminated from further consideration.

The results of the site-specific exposure pathways screening assessment indicated that incidental exposure to onsite contamination in soil and surface water is possible during nonintrusive maintenance activities. Additionally, incidental exposure to contaminated subsurface soils and shallow groundwater is possible if deep excavation/construction activities are conducted in and immediately downgradient from

the source areas at these sites. Onsite workers are the only group of receptors that would likely come into incidental contact with site-related contamination under both current and future land use scenarios at both of these sites. No completed pathway to potential ecological receptors was found.

Estimation of Exposure-Point Risk

The first step in quantifying the risk associated with completed contaminant migration pathways was to estimate what the contaminant concentrations would be at the exposure point. This analysis took into account the time and travel distances that would be required to allow a chemical to migrate from its current location to the point of exposure. An analysis was performed using the SESOIL and Bioplume II models to quantify contaminant leaching and biodegradation, respectively. The effects of these transformation processes and other contaminant characteristics that influence contaminant concentration, mass, mobility, persistence, and toxicity were factored into this numerical analysis. The analysis was performed for two scenarios, natural chemical attenuation alone, and bioventing/biosparging at Site ST14.

After exposure point concentrations were quantitatively estimated, risk to potential receptors was calculated. Risk was quantified using chemical specific toxicity data and chemical intake estimates. It is important to note that this risk assessment took into account cumulative exposure to all fuel related contaminants at the site, not just the COPCs identified during the Plan A screening evaluation. Standard chemical intake variables provided by the US Environmental Protection Agency (USEPA, 1991) were used in the risk estimation calculations. Intake variables defining onsite intrusive construction workers' exposure were different than those used for the nonintrusive industrial worker. For example, the intrusive industrial worker was assumed to remain at the job for an equivalent of only 1 year (instead of the 25 years assumed for the nonintrusive industrial worker). This assumption is based on best professional judgment, as most construction-related/remediation activities at the site would likely not last more than the equivalent of 1 year of continuous exposure. Any necessary remediation activities at the site will not require workers to be constantly present after initial installation activities are complete.

The conclusion the Plan B limited risk assessment was that existing concentrations of all measured compounds in mixed soils and groundwater at both Site ST14 and Site SD13 do not result in hazard quotients greater than the noncarcinogenic threshold limit of 1 for all receptor groups considered. The current or future intrusive worker pathway-specific carcinogenic risk estimate did not exceed the threshold of 1×10^{-6} , however, the cumulative (all pathways) risk estimates are just slightly greater than this threshold. This cumulative risk level has been identified as the target risk level by TNRCC for receptor groups where actual exposure has occurred or may occur. The natural chemical attenuation of the COPCs expected by the year 1998 would reduce the carcinogenic risks to the receptor groups to levels almost (but not exactly) equivalent to the 1×10^{-6} target risk level.

PLAN B TARGET LEVEL EVALUATION

The Plan B limited risk assessment was used as the basis for developing Plan B target concentrations (i.e., SSTLs) for COPCs in impacted media at Site ST14 and Site

SD13. Although the chemical fate and transport analysis performed as part of the limited risk assessment illustrates that natural chemical attenuation processes are expected to reduce COPC concentrations to applicable Plan A target concentrations within a reasonable timeframe (i.e., by the year 2003 in source soils at Site ST14A, by the year 2005 in groundwater underlying Site ST14, and by the year 2007 in groundwater at Site SD13), Plan B target concentrations were developed to identify the shortest possible time required to achieve the desired level of health protection for potential receptor groups at these sites, given the types of exposure that could occur and the mass reducing effects of natural chemical attenuation processes over time. The objective of the Plan B SSTLs was to define the concentration for each COPC that can persist in onsite environmental media and not result in an individual risk greater than 1×10^{-6} for carcinogenic chemicals (benzene and hexachlorobenzene) or an HQ of 1 for noncarcinogenic chemicals (hexachlorobenzene) for each receptor group given the site-specific exposure assumptions incorporated into the Plan B limited risk assessment.

Table D.4 presents the Plan B target concentrations that were developed to be protective of both onsite intrusive and nonintrusive workers and underlying groundwater quality. The maximum measured concentration of benzene in groundwater, the only groundwater COPC, is well below Plan B target concentration of 241 $\mu\text{g/L}$ for dermal exposure. Natural chemical attenuation processes that have been documented to be operating at these sites are expected to further reduce benzene concentrations by the year 1998 (i.e., when the sites are planned to be transferred and used in accordance with the final land use plan). These Plan B target concentrations for groundwater reiterate the findings of the Plan B limited risk assessment: exposure pathways involving groundwater, given the type of exposure that is likely to occur at these sites, do not result in significant human health threats.

However, Table D.4 does indicate that residual concentrations of benzene and possibly hexachlorobenzene in soils may pose an unacceptable risk to both nonintrusive workers (should actual exposure occur as assumed in development of the Plan B target concentrations) and underlying groundwater quality. These results are consistent with the Plan B limited risk assessment. This means that contaminated soils, particularly at Site ST14A, may pose an unacceptable risk to nonintrusive workers should they come into direct contact with impacted soil on a regular basis. The exposure pathways analysis performed as part of the limited risk assessment indicated that these receptors are not likely to be involved in complete exposure pathways including direct contact with impacted site media. However, appropriate exposure controls (i.e., personal protective equipment) or some type of similar low-cost remediation strategy, such as bioventing, may be considered a prudent "insurance" measure to prevent unacceptable risks to this potential receptor group.

Cross-media contamination of groundwater from contaminated soil also was factored into the development of the Plan B target concentrations for soil. The SESOIL model developed for this site indicated that soils at Site ST14A will act as a continuing but diminishing source of groundwater contamination for about 10 years. The Plan B target concentrations are consistent with these earlier model results, although the Plan B levels may overestimate the degree to which contaminants may leach from and dissolve into underlying groundwater at the sites. The target groundwater concentration used in the Plan B derivations was the Plan B target groundwater concentration. Benzene has not been measured in groundwater at concentrations above

its Plan B target concentration. No hexachlorobenzene has been detected in groundwater. These site analytical data suggest that soils are not causing Plan B target groundwater exceedances. However, on the basis of both the SESOIL model results and the Plan B target concentrations for soil that are protective of underlying groundwater quality, some type of soil remediation may be warranted to prevent exceedances of Plan B target groundwater concentrations or at least minimize the addition of contaminant mass to groundwater to ensure that existing plumes stabilize. The latter objective is important to ensure that dissolved contamination does not unexpectedly migrate downgradient toward areas under different exposure controls and/or the unnamed stream and Farmers Branch.

DEVELOPMENT OF REMEDIAL ALTERNATIVES

Given the current and planned land uses and access restrictions enforced at Site ST14, it was decided to pursue implementation of remedial actions that would achieve the Plan B target concentrations and TNRCC cumulative risk thresholds at Site ST14 and SD13.

Three possible remedial alternatives were developed. All three of the alternatives were designed to meet the generic industrial criteria, albeit within different time frames and at different costs. The following remedial techniques were evaluated for inclusion in the remedial alternatives:

- Groundwater monitoring;
- Limited land use controls;
- Groundwater use controls;
- Public education;
- Intrinsic remediation of soil and groundwater contamination;
- Groundwater extraction via vacuum extraction;
- Extracted groundwater treatment with an oil/water separator and air stripping unit;
- Treated groundwater discharge to surface water;
- Abandonment of the subsurface french drain and oil/water separator; and
- Air injection bioventing and biosparging in source areas.

Data from pilot testing of the bioventing and biosparging technologies performed during the risk-based site investigation were used to quantitatively estimate the costs and effectiveness of these technologies. Intrinsic remediation potential was quantified through analysis of geochemical data collected during the site investigation at the site. The Bioplume II model, created for the site during limited risk assessment, was used to quantitatively estimate groundwater contaminant attenuation and migration at the site under different remedial scenarios.

Three remedial alternative were formulated from the possible remedial techniques:

- **Alternative 1** - Intrinsic Remediation with Long-Term Monitoring, French Drain and Oil/Water Separator Abandonment, and Land and Groundwater Use Controls;
- **Alternative 2** - Intrinsic Remediation with Long-Term Monitoring, French Drain and Oil/Water Separator Abandonment, *In Situ* Bioventing and Biosparging at Site ST14A, and Land and Groundwater Use Controls; and
- **Alternative 3** - Intrinsic Remediation with Long-Term Monitoring, French Drain and Oil/Water Separator Abandonment, *In Situ* Bioventing and Biosparging at Site ST14A, Groundwater Removal/Treatment and Soil Vapor Extraction at Site SD13, and Land and Groundwater Use Controls.

All three of the alternatives were evaluated in terms of effectiveness, implementability, and cost. A summary of this evaluation is shown in Table D.5.

RECOMMENDED REMEDIAL ALTERNATIVE

Alternative 2 (Intrinsic Remediation with Long-Term Monitoring, French Drain and Oil/Water Separator Abandonment, *In Situ* Bioventing and Biosparging at Site ST14A, and Land and Groundwater Use Controls) was recommended for the remediation of Site ST14 based on its expected effectiveness in attaining Plan B criteria, its relative simplicity with respect to technical and administrative implementation, and its low overall cost.

Historical decreases in contaminant concentrations and conservative fate and transport modeling indicate that intrinsic remediation with source reduction via *in situ* bioventing will achieve Plan B criteria in approximately 3 years. Bioplume II modeling predicted very limited plume migration, with no chance of off-Base migration. Long-term groundwater monitoring will be used to verify intrinsic remediation and to ensure that contaminants do not migrate to the Base boundary. Limitations on groundwater pumping at this site should not impose a restriction on future airfield land use or operations. Abandonment of the french drain and oil/water separator was prescribed to eliminate the potential contaminant pathway from groundwater to surface water. The following sections provide additional detail on the implementation of this alternative.

Regulatory Approval

The draft final RAP for the risk-based remediation of Site ST14 was issued to the TNRCC for review in July of 1997. The TNRCC has approved the remedial actions proposed for Site ST-14 and a final decision on Site SD-13 is pending.

Remedial Action Implementation and Long-Term Monitoring

As prescribed in the RAP, an *in situ* bioventing/biosparging system was installed at Site ST14A in April 1996 to remediate residual soil contamination at the site. The 14 well system is treating an estimated area of 54,000 square feet. It is estimated that the system will be operating for 2 years to lower soil contaminant concentrations to levels

where there is no longer a risk on onsite workers or underlying groundwater. At the conclusion of 2 years of operation, confirmatory soil sampling will be performed at Site ST14A to ensure that soil contaminant concentrations have been reduced to acceptable levels. Additionally, the french drain and oil/water separator were removed from Site SD13 in June 1996. This effectively eliminated the potential that contaminated groundwater could be released to the unnamed stream and Farmers Branch and impact surface water quality.

As part of the RAP, a long-term monitoring plan (LTMP) was developed for the site to monitor the implementation and progress of the recommended remedial action. This LTMP prescribes monitoring and maintenance schedules for the bioventing/bioventing system. Verification soil sampling is described in detail in the LTMP. Groundwater monitoring schedules and sampling protocols were also incorporated into the LTMP for the site. Long-term groundwater monitoring is essential to verify the progress of intrinsic remediation. Careful implementation of the LTMP is a key component of the RAP for the site. The LTMP for the site calls for annual groundwater sampling at a total of 18 sampling locations, including two sentry wells to track the horizontal and vertical movement of the plume, and three downgradient point-of-compliance (POC) wells to ensure that contaminants are not moving at a rate that could result in off-Base migration. Annual sampling was considered appropriate by all parties given the current contaminant concentrations and limited contaminant migration observed to date. The first round of annual groundwater sampling is scheduled for the fall of 1996.

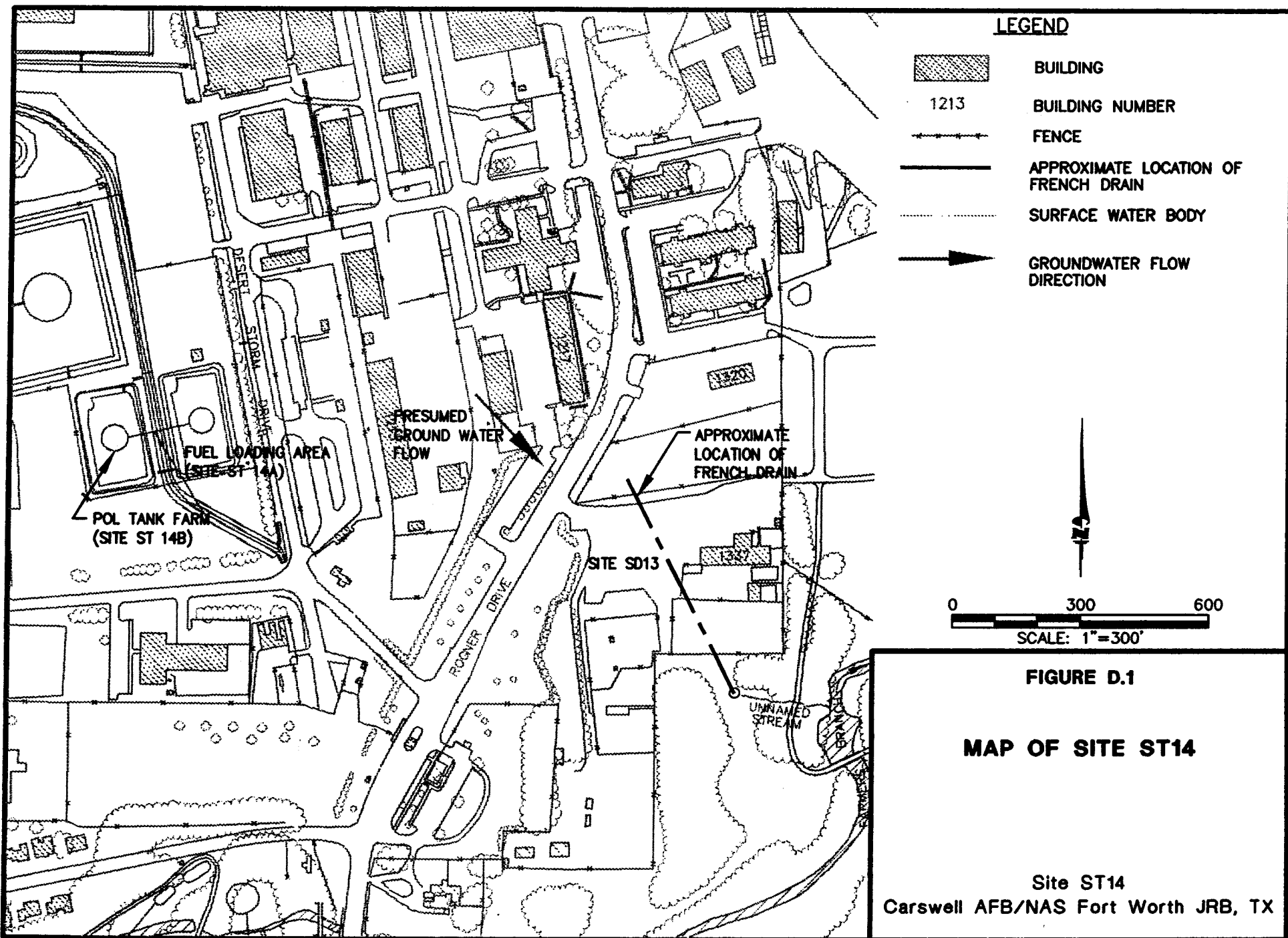
Another component of the LTMP, land use verification, will be accomplished by maintaining communication between the Base, TNRCC, and current and future site occupants. The risk-based remediation of Site ST14 Crash Site is based upon an industrial land-use scenario at the site. If land use at the site changes unexpectedly (i.e., the site is released for residential occupancy before appropriate Plan B criteria are achieved), site conditions and associated risk must be reevaluated accordingly. Visual inspections of the site also will be made during annual groundwater sampling site visits to ensure that no nonindustrial activities are occurring at the site.

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**TABLE D.1
FIXED-BASE AND FIELD METHODS BY ANALYTE
SITE ST14, CARSWELL AFB/NAS FORT WORTH JRB, TEXAS**

Analyte	Matrix	Analytical Method	Field or Fixed-Base
Benzene	Soil Gas	TO3	Fixed-Base
Toluene	Soil Gas	TO3	Fixed-Base
Ethylbenzene	Soil Gas	TO3	Fixed-Base
Xylene (Total)	Soil Gas	TO3	Fixed-Base
Petroleum Hydrocarbons	Soil Gas	TO3	Fixed-Base
Total Extractable Hydrocarbons	Soil and Water	M8015	Fixed-Base
Total Volatile Hydrocarbons	Soil and Water	M8015	Fixed-Base
Benzene	Soil and Water	SW8020	Fixed-Base
Toluene	Soil and Water	SW8020	Fixed-Base
Ethylbenzene	Soil and Water	SW8020	Fixed-Base
Xylene (Total)	Soil and Water	SW8020	Fixed-Base
1,2,3-Trimethylbenzene	Soil and Water	SW8020	Fixed-Base
1,2,4-Trimethylbenzene	Soil and Water	SW8020	Fixed-Base
1,3,5-Trimethylbenzene	Soil and Water	SW8020	Fixed-Base
1,3-Dichlorobenzene	Soil and Water	SW8270	Fixed-Base
1,4-Dichlorobenzene	Soil and Water	SW8270	Fixed-Base
1,2-Dichlorobenzene	Soil and Water	SW8270	Fixed-Base
Hexachloroethane	Soil and Water	SW8270	Fixed-Base
Naphthalene	Soil and Water	SW8270	Fixed-Base
2-Methylnaphthalene	Soil and Water	SW8270	Fixed-Base
Acenaphthylene	Soil and Water	SW8270	Fixed-Base
Acenaphthene	Soil and Water	SW8270	Fixed-Base
Dibenzofuran	Soil and Water	SW8270	Fixed-Base
Fluorene	Soil and Water	SW8270	Fixed-Base
Hexachlorobenzene	Soil and Water	SW8270	Fixed-Base
Phenanthrene	Soil and Water	SW8270	Fixed-Base
Anthracene	Soil and Water	SW8270	Fixed-Base
Fluoranthene	Soil and Water	SW8270	Fixed-Base
Pyrene	Soil and Water	SW8270	Fixed-Base
Chrysene	Soil and Water	SW8270	Fixed-Base
Benzo(b)fluoranthene	Soil and Water	SW8270	Fixed-Base
Benzo(k)fluoranthene	Soil and Water	SW8270	Fixed-Base
Benzo(a)pyrene	Soil and Water	SW8270	Fixed-Base
Indeno(1,2,3-cd)pyrene	Soil and Water	SW8270	Fixed-Base
Dibenzo(a,h)anthracene	Soil and Water	SW8270	Fixed-Base
Benzo(g,h,i)perylene	Soil and Water	SW8270	Fixed-Base
Phenol	Soil and Water	SW8270	Fixed-Base
Pentachlorophenol	Soil and Water	SW8270	Fixed-Base
2,4,5-Trichlorophenol	Soil and Water	SW8270	Fixed-Base

TABLE D.1 (Concluded)
FIXED-BASE AND FIELD METHODS BY ANALYTE
SITE ST14, CARSWELL AFB/NAS FORT WORTH JRB, TEXAS

Compound	Matrix	Analytical Method	Field or Fixed-Base
Trichloroethene	Water	SW8010	Fixed-Base
pH	Soil	SW9045	Fixed-Base
Total Organic Carbon	Soil	SW9060	Fixed-Base
Moisture, Percent	Soil	E160.3	Fixed-Base
Phosphorus, Total Orthophosphate (as P)	Soil	E300.0	Fixed-Base
Alkalinity, Total (as CaCO ₃)	Soil	E310.1	Fixed-Base
Nitrogen, Total Kjeldahl	Soil	E351.3	Fixed-Base
Iron	Soil	SW6010	Fixed-Base
pH	Water	FPH	Field
Redox Potential	Water	FREDOX	Field
Temperature	Water	FTEMP	Field
Iron	Water	H8008	Field
Nitrate	Water	H8039	Field
Nitrite	Water	H8040	Field
Sulfate	Water	H8051	Field
Hydrogen Sulfide	Water	H8131	Field
Iron, Ferrous	Water	H8146	Field
Alkalinity, Total (as CaCO ₃)	Water	H8221	Field
Carbon Dioxide	Water	H8223	Field
Manganese	Water	HMANG	Field
Carbon Dioxide	Water	COU-O2	Fixed-Base
Methane	Water	RSK175	Fixed-Base

TABLE D.2
COMPARISON TO HEALTH-BASED PLAN A TARGET CONCENTRATIONS
SITE ST14, CARSWELL AFB/NAS FORT WORTH JRB, TEXAS

Compound	Units	Max Conc. Bioventing Pilot Test 1993	Maximum Concentration RFI 1994	Maximum Concentration Risk-Based 1994/1995	PLAN A TARGET CONCENTRATION				
					Target GW Concentration ^{a/} Noncarcinogenic	Target GW Concentration ^{b/} Carcinogenic	Groundwater Protective Soil ^{c/} Concentration	Health-Based Soil Conc. ^{d/} Noncarcinogenic	Health-Based Soil Conc. ^{e/} Carcinogenic
Soil									
Volatile Organic Compounds									
1,2,3,4-Tetramethylbenzene	mg/kg	-	-	19	NA	NA	-	-	-
1,2,3-Trimethylbenzene	mg/kg	-	-	9.6	NA	NA	-	-	-
1,2,4-Trimethylbenzene	mg/kg	-	-	28	NA	NA	-	-	-
1,3,5-Trimethylbenzene	mg/kg	-	-	14	NA	NA	-	-	-
Acetone	mg/kg	-	0.034	-	NA	NA	-	2.04E+05	-
Benzene	mg/kg	67	-	0.0024	NA	NA	7.40E-01	-	7.90E-01
Chlorobenzene	mg/kg	-	-	2.4	NA	NA	9.73E+01	4.47E+02	-
Ethylbenzene	mg/kg	17	-	9.1	NA	NA	8.35E+02	3.36E+03	-
Methylene Chloride	mg/kg	-	0.016	-	NA	NA	-	1.22E+05	7.63E+02
Toluene	mg/kg	54	-	2.5	NA	NA	5.03E+02	3.26E+03	-
Xylenes (Total)	mg/kg	52	-	56	NA	NA	9.68E+02	9.68E+02	-
Semivolatile Organic Compounds									
1,2,4-Trichlorobenzene	mg/kg	-	-	0.053	NA	NA	7.40E+03	1.28E+04	-
1,4-Dichlorobenzene	mg/kg	-	-	0.053	NA	NA	1.23E+02	5.00E+04	6.66E+02
2-Chlorophenol	mg/kg	-	-	0.1	NA	NA	3.00E+02	1.02E+00	-
2-Methylnaphthalene	mg/kg	-	-	0.46	NA	NA	-	-	-
4-Chloro-3-methylphenol	mg/kg	-	-	0.098	NA	NA	-	-	-
Acenaphthene	mg/kg	-	-	0.059	NA	NA	3.14E+02	3.14E+02	-
Di-n-butylphthalate	mg/kg	-	-	0.068	NA	NA	1.12E+03	2.04E+05	-
Fluorene	mg/kg	-	-	0.025	NA	NA	2.47E+02	2.47E+02	-
Hexachlorobenzene	mg/kg	-	-	0.46	NA	NA	3.14E+03	1.63E+03	3.61E-01
N-Nitroso-di-n-propylamine	mg/kg	-	-	0.054	NA	NA	1.63E+01	-	8.18E-01
Naphthalene	mg/kg	-	-	2.9	NA	NA	3.89E+02	7.82E+02	-
Phenol	mg/kg	-	-	0.12	NA	NA	1.95E+01	1.22E+06	-
Pyrene	mg/kg	-	-	0.049	NA	NA	9.90E+01	9.90E+01	-
Petroleum Hydrocarbons									
Petroleum Hydrocarbons	mg/kg	9300	-	8800	NA	NA	-	-	-
Total Extractable Hydrocarbons	mg/kg	-	-	2200	NA	NA	-	-	-

TABLE D.2 (Continued)
COMPARISON TO HEALTH-BASED PLAN A TARGET CONCENTRATIONS
SITE ST14, CARSWELL AFB/NAS FORT WORTH JRB, TEXAS

Compound	Units	Max Conc. Bioventing Pilot Test 1993	Maximum Concentration RFI 1994	Maximum Concentration Risk-Based 1994/1995	PLAN A TARGET CONCENTRATION				
					Target GW Concentration ^{a/} Noncarcinogenic	Target GW Concentration ^{b/} Carcinogenic	Groundwater Protective Soil ^{c/} Concentration	Health-Based Soil Conc. ^{d/} Noncarcinogenic	Health-Based Soil Conc. ^{e/} Carcinogenic
Groundwater									
Volatile Organic Compounds									
1,2,3,4-Tetramethylbenzene	mg/L	-	-	0.058	-	-	NA	NA	NA
1,2,3-Trimethylbenzene	mg/L	-	-	0.062	-	-	NA	NA	NA
1,2,4-Trimethylbenzene	mg/L	-	-	0.071	-	-	NA	NA	NA
1,3,5-Trimethylbenzene	mg/L	-	-	0.052	-	-	NA	NA	NA
Benzene	mg/L	-	-	0.11	-	2.94E-03	NA	NA	NA
Bromodichloromethane	mg/L	-	0.0038	-	7.30E-01	1.37E-03	NA	NA	NA
Chlorobenzene	mg/L	-	-	0.014	7.30E-01	-	NA	NA	NA
Chloroform	mg/L	-	0.0052	-	3.65E-01	1.40E-02	NA	NA	NA
Dibromochloromethane	mg/L	-	0.00047	-	7.30E-01	1.01E-03	NA	NA	NA
Ethylbenzene	mg/L	-	0.409	0.038	3.65E+00	-	NA	NA	NA
Methylene Chloride	mg/L	-	0.012	-	2.19E+00	1.14E-02	NA	NA	NA
Tetrachloroethene	mg/L	-	0.0091	-	3.65E-01	-	NA	NA	NA
Toluene	mg/L	-	-	0.069	7.30E+00	-	NA	NA	NA
Trichloroethene	mg/L	-	-	0.0014	-	-	NA	NA	NA
Xylenes (Total)	mg/L	-	1.089	0.11	7.30E+01	-	NA	NA	NA
Semivolatile Organic Compounds									
2-Methylnaphthalene	mg/L	-	-	8	-	-	NA	NA	NA
Dibenzofuran	mg/L	-	-	1	-	-	NA	NA	NA
Naphthalene	mg/L	-	-	5	1.46E+00	-	NA	NA	NA
Petroleum Hydrocarbons									
Methane	mg/L	-	5.3	-	-	-	NA	NA	NA
Petroleum Hydrocarbons	mg/L	-	111,000	5.2	-	-	NA	NA	NA
Total Extractable Hydrocarbons	mg/L	-	-	25	-	-	NA	NA	NA
Total Volatile Hydrocarbons	mg/L	-	184,000	-	-	-	NA	NA	NA

TABLE D.2 (Continued)
COMPARISON TO HEALTH-BASED PLAN A TARGET CONCENTRATIONS
SITE ST14, CARSWELL AFB/NAS FORT WORTH JRB, TEXAS

Compound	Units	Max Conc. Bioventing Pilot Test 1993	Maximum Concentration RFI 1994	Maximum Concentration Risk-Based 1994/1995	PLAN A TARGET CONCENTRATION				
					Target GW Concentration ^{a/} Noncarcinogenic	Target GW Concentration ^{b/} Carcinogenic	Groundwater Protective Soil ^{c/} Concentration	Health-Based Soil Conc. ^{d/} Noncarcinogenic	Health-Based Soil Conc. ^{e/} Carcinogenic
Surface Water									
Volatile Organic Compounds									
1,2,3,4-Tetramethylbenzene	mg/L	-	-	33.3	NA	NA	NA	NA	NA
1,2,4-Trimethylbenzene	mg/L	-	-	2.1	NA	NA	NA	NA	NA
1,3,5-Trimethylbenzene	mg/L	-	-	0.7	NA	NA	NA	NA	NA
Chlorobenzene	mg/L	-	-	0.9	1.56E+03	--	NA	NA	NA
Ethylbenzene	mg/L	-	-	0.5	7.80E+03	--	NA	NA	NA
Toluene	mg/L	-	-	1.5	1.56E+04	--	NA	NA	NA
Xylenes (Total)	mg/L	-	-	1.2	1.56E+05	--	NA	NA	NA
Semivolatile Organic Compounds									
2-Methylnaphthalene	mg/L	-	-	4	NA	NA	NA	NA	NA
Petroleum Hydrocarbons									
Total Extractable Hydrocarbons	mg/L	-	-	0.5	NA	NA	NA	NA	NA
Other Analyses									
Total Organic Carbon	mg/L	-	-	77.9	NA	NA	NA	NA	NA

Note: Maximum measured site concentrations that exceed health-based Plan A target concentrations are identified.

Footnotes:

- ^{a/} Groundwater concentrations for noncarcinogen.
- ^{b/} Groundwater concentration for carcinogens.
- ^{c/} Soil concentration that will be protective of underlying groundwater for noncarcinogens.
- ^{d/} Health-protective soil concentration for industrial/commercial sites (noncarcinogens).
- ^{e/} Health-protective soil concentration for industrial/commercial sites (carcinogens).

TABLE D.3
SCREENING LEVEL EVALUATION OF GROUNDWATER
AND SURFACE WATER ANALYTES FOR ENVIRONMENTAL PROTECTION
SITE ST14, CARSWELL AFB/NAS FORT WORTH JRB

Analyte	Maximum Concentration ^{a/}	Units ^{b/}	MCL ^c	Water Quality Criteria ^{d/}	
				Freshwater Acute Criteria ^{e/}	Freshwater Chronic Criteria
GROUNDWATER					
Volatile Organic Compounds					
1,2,3,4-Tetramethylbenzene	0.058	mg/L	--	--	--
1,2,3-Trimethylbenzene	0.062	mg/L	--	--	--
1,2,4-Trimethylbenzene	0.071	mg/L	--	--	--
1,3,5-Trimethylbenzene	0.052	mg/L	--	--	--
Benzene	0.11	mg/L	0.005	5.3	--
Bromodichloromethane	0.0038	mg/L	0.08	--	--
Chlorobenzene	0.014	mg/L	--	--	--
Chloroform	0.0052	mg/L	0.08	28.9	1.24
Dibromochloromethane	0.00047	mg/L	--	--	--
Ethylbenzene	0.409	mg/L	0.7	32	--
Methylene Chloride	0.012	mg/L	0.005	--	--
Tetrachloroethene	0.0091	mg/L	0.005	5.28	0.84
Toluene	0.069	mg/L	1	17.5	--
Trichloroethene	0.0014	mg/L	0.005	45	21.9
Xylenes (Total)	1.089	mg/L	10	--	--
Semivolatile Organic Compounds					
2-Methylnaphthalene	0.008	mg/L	--	--	--
Dibenzofuran	0.001	mg/L	--	--	--
Naphthalene	0.053	mg/L	--	2.3	0.62
Petroleum Hydrocarbons					
Methane	5.3	mg/L	--	--	--
Petroleum Hydrocarbons	111000	mg/L	--	--	--
Total Extractable Hydrocarbons	25	mg/L	--	--	--
Total Volatile Hydrocarbons	184000	mg/L	--	--	--
SURFACE WATER					
Volatile Organic Compounds					
1,2,3,4-Tetramethylbenzene	0.0333	mg/L	--	--	--
1,2,4-Trimethylbenzene	0.0021	mg/L	--	--	--
1,3,5-Trimethylbenzene	0.0007	mg/L	--	--	--
Benzene	< MDL ^{e/}	mg/L	0.005	5.3	--
Chlorobenzene	0.0009	mg/L	--	--	--
Ethylbenzene	0.0005	mg/L	0.7	32	--
Methylene Chloride	0.0069	mg/L	--	--	--
Toluene	0.0015	mg/L	1	17.5	--
Xylenes (Total)	0.0012	mg/L	10	--	--

TABLE D.3 (Concluded)
SCREENING LEVEL EVALUATION OF GROUNDWATER
AND SURFACE WATER ANALYTES FOR ENVIRONMENTAL PROTECTION
SITE ST14, CARSWELL AFB/NAS FORT WORTH JRB

Analyte	Maximum Concentration ^{a/}	Units ^{b/}	MCL ^{c/}	Water Quality Criteria ^{d/}	
				Freshwater Acute Criteria ^{d/}	Freshwater Chronic Criteria
Semivolatile Organic Compounds					
2-Methylnaphthalene	0.004	mg/L	--	--	--

Note: Shaded chemicals represent those that exceed either one or both of the comparison criteria.

^{a/} Maximum concentrations were obtained from both the 1993 RFI and 1994 risk-based investigation sampling

^{b/} mg/L = milligrams per liter.

^{c/} MCL = Maximum Contaminant Level. Maximum permissible level of a contaminant in water which is delivered to any user of a public water system.

EPA(1994) Drinking Water Regulations and Health Advisories.

^{d/} Freshwater acute and chronic water quality criteria from EPA (1991).

^{e/} "--" = reference information not available; unable to make comparison.

^{f/} MDL = method detection limit. For benzene, the MDL = 0.000283 mg/L.

TABLE D.4
COMPARISON TO HEALTH-BASED PLAN B TARGET CONCENTRATIONS
SITE ST14, CARSWELL AFB/NAS FORT WORTH JRB, TEXAS

Compound	Units	Maximum Concentration From 1993-1995	1998 Projected Concentration ^{a/}		Plan B Groundwater Protective Soil Concentration ^{d/}		Plan B Health-Based Concentration ^{g/}			
			Natural Attenuation ^{b/}	Natural Attenuation with Bioventing ^{c/}	Intrusive Workers		Intrusive ^{h/}		Nonintrusive ^{i/}	
					RME ^{e/}	CT ^{f/}	RME ^{e/}	CT ^{f/}	RME ^{e/}	CT ^{f/}
Soil										
Benzene	mg/kg	67	49.6	BDL ^{j/}	10.8	13.4	101	469	6.27	84.2
Hexachlorobenzene	mg/kg	0.46	0.239	BDL ^{j/}	0.021	0.026	0.497	1.29	0.061	0.869
Groundwater										
Benzene	mg/L	0.11	0.1	0.0604	NA ^{k/}	NA	0.241	0.298	NA	NA

Note: Measured and projected site concentrations that exceed Plan B target concentrations are identified by shading.

Footnotes:

- ^{a/} Modeled residual concentration that will be present in affected environmental media in 1998.
- ^{b/} Modeled residual concentration in soil and groundwater in 1998 as a result of natural chemical attenuation processes only.
- ^{c/} Modeled residual concentration in soil and groundwater in 1998 as a result of bioventing source soils and natural chemical attenuation processes.
- ^{d/} Derived soil concentrations that prevent leachate generation above Plan B target groundwater concentrations.
- ^{e/} RME = reasonable maximum exposure; used RME assumptions to derive Plan B target concentration.
- ^{f/} CT = central tendency; used CT assumptions to derive Plan B target concentration.
- ^{g/} Calculated health-based soil concentration to prevent carcinogenic and/or systemic toxic impacts to onsite workers.
- ^{h/} Intrusive worker assumed to be exposed to soils via dermal contact, incidental ingestion of soil, and inhalation of volatilizing chemicals and suspended contaminant soil particulates and exposed to groundwater via dermal contact only.
- ^{i/} Nonintrusive worker assumed to be exposed to soils via dermal contact and incidental ingestion only.
- ^{j/} BDL = below detection limit.
- ^{k/} NA = not applicable.

TABLE D.5
SUMMARY OF REMEDIAL ALTERNATIVE EVALUATION
SITE ST14, CARSWELL AFB/NAS FORT WORTH JRB, TEXAS

Remedial Alternative	Effectiveness	Implementability	Present Worth Cost Estimate
Alternative 1			\$228,000
<ul style="list-style-type: none"> -Natural Chemical Attenuation -French Drain Abandonment -Oil/Water Separator Abandonment -Long-Term Monitoring -Land and Groundwater Use Controls 	Contaminant mass, volume, and toxicity will gradually be reduced by intrinsic remediation alone. Plan B target levels attained at Site ST14 in approximately 8 years.	Technically simple and easy to implement. Long-term groundwater monitoring for about 10 years is required. Groundwater use restrictions need to be implemented and may prevent recreational/open space land use at Site SD13 for 10 years. Requires public education.	
Alternative 2			\$278,900
<ul style="list-style-type: none"> -Natural Chemical Attenuation -French Drain Abandonment -Oil/Water Separator Abandonment -<i>In Situ</i> Bioventing/Biosparging at Site ST14A -Long-Term Monitoring -Land and Groundwater Use Controls 	Similar to Alternative 1, with the addition of bioventing for 2 years to increase source soils contaminant removal and degradation. Pilot testing indicates bioventing will significantly remove benzene from unsaturated soils. Plan B target levels attained at Site ST14 in approximately 2 years.	Long-term groundwater monitoring for 5 years is expected. The bioventing system is expected to operate for 2 years. This systems will require weekly monitoring. Groundwater and land use restrictions would be the same as Alternative 1. Positive public perception. Requires public education.	
Alternative 3			\$419,000
<ul style="list-style-type: none"> -Natural Chemical Attenuation -French Drain Abandonment -Oil/Water Separator Abandonment -<i>In Situ</i> Bioventing at Site ST14A -Groundwater Removal/Treatment and SVE at Site SD13. -Long-Term Monitoring -Land and Groundwater Use Controls 	Similar to Alternative 2, with additional groundwater removal and treatment. Plan B target levels attained at Site ST14 in approximately 2 years.	Long-term groundwater monitoring for 4 years is expected. Operation of the treatment system will require weekly monitoring. Lengthy lead time required for design and installation of extraction/treatment system. Positive public perception.	

APPENDIX B

SITE CHARACTERIZATION

B.1 OVERVIEW

This appendix provides a practical approach for completing a "progressive" or "observational" site investigation at petroleum-contaminated sites. The term "progressive" is used because the most useful and cost-effective site investigations are seldom achieved by rigidly following a work plan. Instead they "progress" during fieldwork as real-time field results from each soil gas sample, cone penetrometer push, soil boring, or groundwater sample reveals different aspects of the site geology, hydrology, and contaminant distribution. Consequently, the most effective work plan is one which allows the investigation contractor the flexibility to respond to the "surprises" that can, and frequently do, occur at most sites. A progressive site investigation also must focus on collecting quality data that not only define the extent of contamination, but also provide evidence of natural chemical attenuation processes and establish the effectiveness of engineered remediation technologies that may play a role in the cleanup of the site. The purpose of this appendix is to describe several important steps in the planning and execution of a site investigation to support risk-based remediation decisions.

B.2 REVIEW OF EXISTING SITE DATA

At many sites, previous site investigation data may be available and are very useful for completing a risk-based corrective action. Historical data are particularly valuable in establishing that natural attenuation processes are reducing risks associated with chemical contamination. Data should be organized by environmental medium (e.g., soil, groundwater, soil gas, etc.) and arranged in tabular format to complement a site map that shows sampling locations and key cultural and natural site features. Laboratory detection limits and any data qualifiers should be included on the table. The quality of laboratory data is often an issue when detection limits are the same order of magnitude as the RBSLs. Additional comments on data quality are included in Appendix B.5.2. Field data such as groundwater reduction/oxidation (redox) conditions, dissolved oxygen (DO), and dissolved metals such as iron all are potentially useful for the study of natural chemical attenuation and also should be organized in tables. Existing data should be reviewed to answer the following key questions:

- Where is the source of contamination and has it been removed?
- Is the date of release known and has the leak been stopped?
- What media have been impacted by the release (e.g., soil, groundwater, soil gas)?

- Does free product remain at the site?
- Has the geology and soil stratigraphy been defined (e.g., is a site cross-appendix available)?
- Have the groundwater flow direction and gradient been determined?
- Has the full extent of soil and groundwater contamination been defined?
- Is there preliminary evidence of natural chemical attenuation?
- What are the current and planned future land uses at and near the site?
- Are there any immediate risks to human health or the environment?

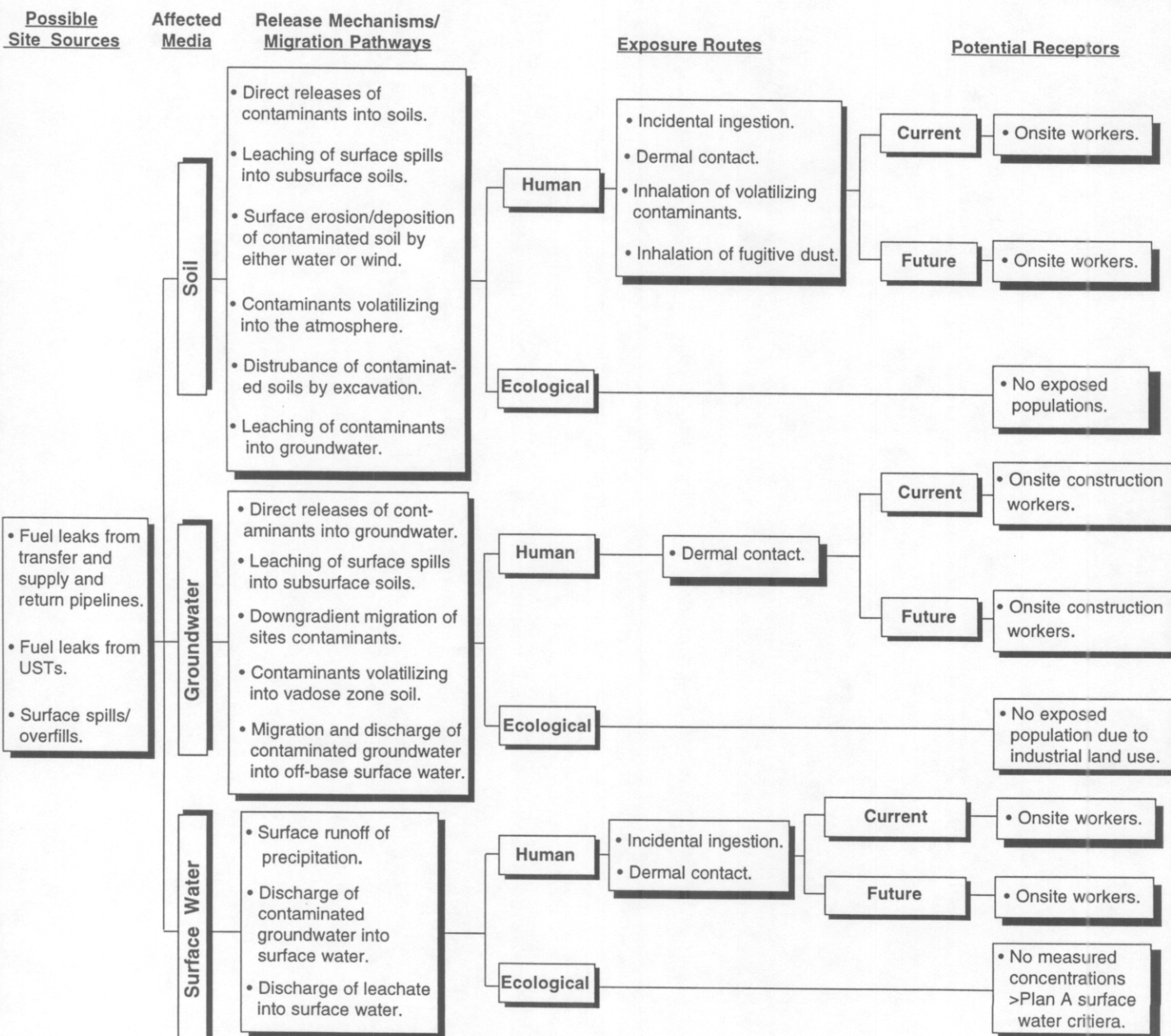
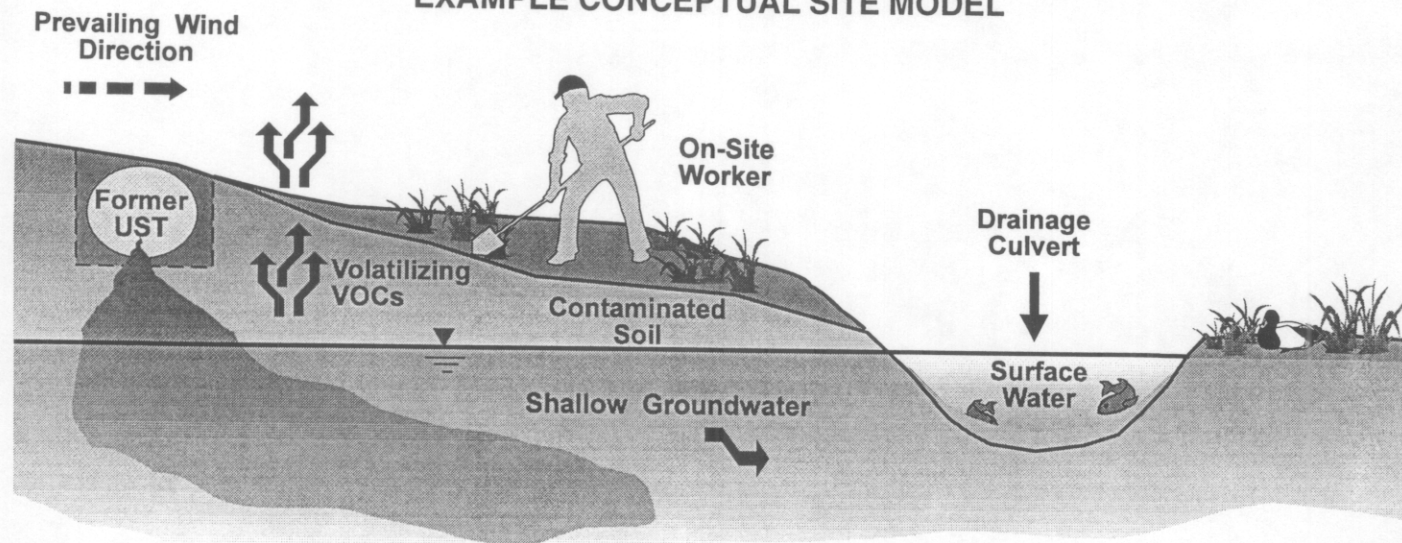
If any of these questions cannot be answered, additional characterization may be required. A useful method for determining the completeness of site data is to construct a preliminary conceptual site model (CSM).

B.3 CONSTRUCTING A PRELIMINARY CONCEPTUAL SITE MODEL

Section 2 described a basic CSM consisting of three primary components: a source of contamination, a contaminant migration pathway or pathways from the source to receptors, and potential receptors. Figure B.1 illustrates a CSM for a typical JP-4 UST leak in an unpaved commercial or industrial area. The primary contaminant source is the UST; the secondary source is the soil contaminated with JP-4 residuals (with no remaining free product). Potential exposure pathways include soil vapor migration to the atmosphere, direct human or ecological receptor contact with contaminated soils, and ingestion or dermal contact with impacted shallow groundwater. There is surface water near the site, so aquatic receptors must also be considered if the plume has the potential to migrate to the surface water body.

A site visit normally is required to properly complete the CSM. To be conservative, the preliminary CSM should account for all possible pathways and receptors given the current and likely future land uses. Often at military facilities scheduled for closure, the future land use may differ from the current land use. In such situations the most conservative expected land use should be used to complete the site model. In the risk-based remediation process, site characterization is used to first determine if a completed pathway exists, and if so, to estimate the exposure-point concentrations of COPCs. Existing site data should be reviewed to identify which potential pathways cannot be evaluated due to a lack of quantitative chemical data for that environmental medium. For example, one pathway that is frequently overlooked is the exposure of site workers to soil vapors during excavation activities. One common data gap is the lack of soil gas data to quantify the concentration of specific VOCs (generally BTEX). A complete CSM will help ensure that all the data required for risk evaluation are gathered in one field mobilization.

FIGURE B.1
EXAMPLE CONCEPTUAL SITE MODEL



B.4 REQUIRED DATA FOR MAKING RISK-BASED REMEDIATION DECISIONS

Table B.1 provides the site investigation data that generally will be needed to complete the risk-based remediation evaluation process. This list was generated from several sources including three AFCEE technical protocols for intrinsic remediation, bioventing, and bioslurping (Wiedemeier *et al.*, 1995; Hinchey *et al.*, 1992; Kittle *et al.*, 1995), and ASTM (1994) RBCA. Table B.1 is applicable for several petroleum types, including JP-4, JP-8, gasoline, and diesel/heating oils. Table B.1 has divided data requirements into three broad categories:

- General Site Information;
- Contaminant Distribution Analysis; and
- Fate and Transport with Environmental Media.

Site characterization requirements should be modified based on the fuel type and the data gaps identified in the preliminary CSM. For example, soil gas sampling may not be required at heating oil sites due to the low levels of volatile compounds found in unweathered heating oil. However, if the spill occurred directly beneath an occupied building, ambient air sampling inside the building should be completed to show that this pathway does not exist or is insignificant.

B.5 DEVELOPING A WORK PLAN FOR SITE CHARACTERIZATION

Once additional site characterization requirements have been defined, a work plan is generally required to coordinate field sampling activities and to gain regulatory approval for the field investigation. The purpose of this appendix is to outline the primary requirements of a work plan and to offer recommendations on how to maximize the useful data generated from a single field mobilization. Figure B.2 illustrates the primary components of a complete work plan.

B.5.1 Establishing Regulatory Requirements

Because the ultimate judge of any corrective action is normally a regulatory official, it is important to determine the criteria for success as defined by your specific regulatory agency. It is critical that any written guidance provided by the regulatory agency be referenced and used to guide the work plan development. Verbal dialogue with regulatory officials may provide short-term guidance, but written guidance has a much better chance of being honored when your regulatory point-of-contact changes (which generally happens at least once during the life of each project). Before starting the work plan, call the regulatory agency to make sure that the latest regulatory guidance has been provided.

**TABLE B.1
REQUIRED SITE CHARACTERIZATION DATA FOR RISK-BASED REMEDIATION
DECISIONS**

General Site Information: Scaled site map showing existing sampling points and surface features.
 Local surface hydrology
 Source location, type and estimated volume of fuel released.
 Vadose zone thickness and geology
 Estimated volume of soil contamination or free product
 Depth to groundwater, thickness of aquifer, flow direction
 Aquifer pump test or slug test data, or well yields
 General aquifer quality and local groundwater uses
 Area of contaminated plume
 Current land use and onsite receptors, potential pathways
 Ecological receptors or sensitive habitats - (e.g., wetlands or surface waters)
 Future land use plans or local zoning

Chemical Analyses to Determine Contaminant Distribution

MEDIA

Fuel Type	Soil/Sediment	Soil Gas/Flux Test	Groundwater/Surface Water	Free Product
Gasoline	BTEX SW5035/SW8021B TEL* TPH SW5035/SW8015B	TVH (Field) BTEX USEPA TO-3	BTEX SW8021B MTBE SW8021B TEL*	BTEX SW8021B MTBE SW8021B TEL*
* Only if leaded gasoline suspected				
JP-4/JP-8	BTEX SW5035/SW8021B Naphthalene SW8310 or SW8270C*** TPH SW8015B	TVH (Field) BTEX USEPA TO-3	BTEX SW8021B Naphthalene SW8310 or SW8270C***	BTEX SW8021B Naphthalene SW8310 or SW8270C***
Diesel/Light fuels	BTEX SW5035/SW8021B PAHs SW8270C TPH SW8015B	TVH (Field)	BTEX SW8021B PAHs	BTEX SW8021B SW8270C
Heavy Fuel Oils (No.6)	PAHs SW8270C TPH SW8015B		PAHs SW8270C	PAHs SW8270C

* Tetraethyl Lead

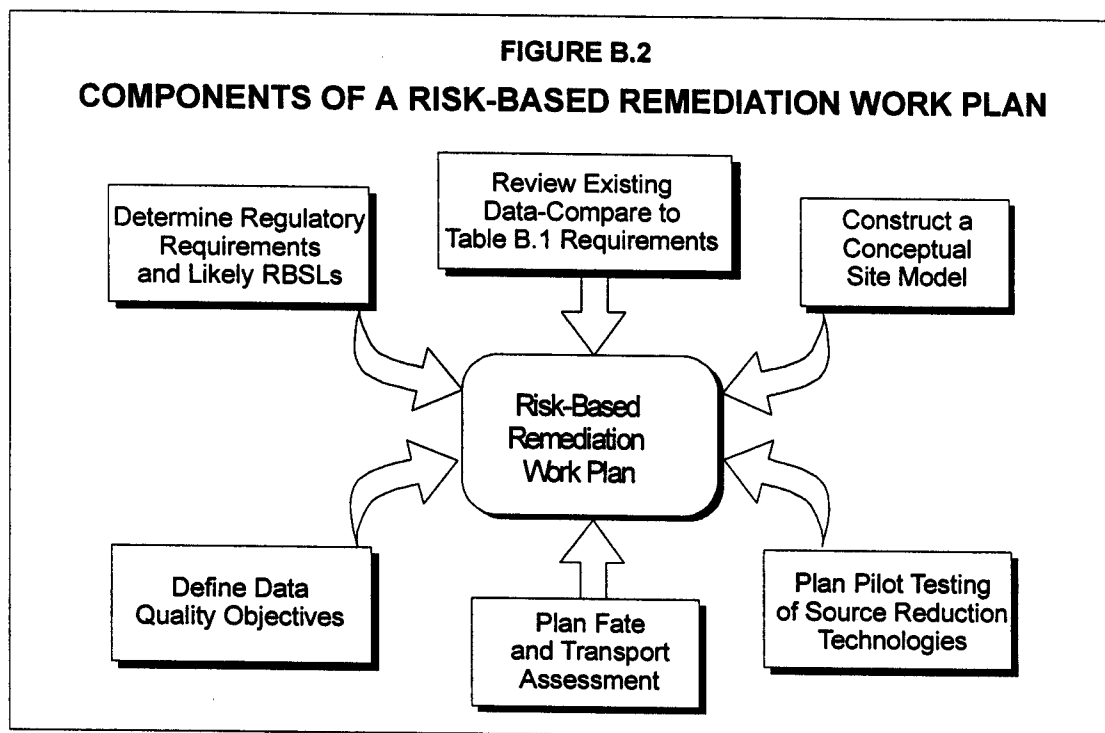
*** Depends on analytical detections limits required

Analysis to Determine Fate and Transport/Intrinsic Remediation Potential

Surface Water	Soil/Sediment	Soil Gas	Groundwater	Free Product
Dissolved O ₂ Stream Flow Lake Volume Surface Area Water Level Seasonal Flow Dynamics	Moisture(ASTM D-2216) Background TOC** (Mod SW9060) Grain Size Analysis (ASTM D422) TKN (USEPA 351.4)	O ₂ /CO ₂	Temperature/pH (Field) Dissolved O ₂ (Field) Redox (Field) Alkalinity (Hach) Nitrate/Nitrite (Hach) Sulfate/Sulfide (Hach) FE ⁺² & Mn ⁺² (Hach) Methane RSKSOP 175 Hydraulic Conductivity Hydraulic Gradients Seasonal water level fluctuations	Product Thickness and Buildup Test at each well

** Must analyze sample from an uncontaminated area

Regulatory guidance regarding RBSLs is particularly important because this will drive the types of analysis required and method detection limits (MDLs) to be specified in the work plan. Some states still require TPH analysis using a variety of different analytical methods. Many states discourage the use of low-cost groundwater sampling devices such as Hydropunch™, and will only accept groundwater data from wells installed by a driller licensed in their state. Well completion and survey requirements also vary, and some sites in heavy traffic areas require special concrete reinforcements around flush-mounted wells. Understanding these unique requirements in the planning stage will ensure that the data gathered will be acceptable and useful.



B.5.2 Defining Data Quality Objectives

One of the most important appendixes in any work plan is the one in which the data quality objectives (DQOs) for the risk-based decision making process are described. DQOs are specified in the work plan to ensure that the number of samples and level of quality assurance (QA) and quality control (QC) for each analysis are suitable to support the end use of the data. For example, if the end use of soil sampling data is to determine the extent of fuel contamination at a site, only a basic level of laboratory QA/QC will be required. In contrast, if groundwater data are going to be used to ensure that an RBSL of 5 ppb has not been exceeded at a base boundary, much more sophisticated sampling and analysis procedures will be required. DQOs should be gathered from several sources including:

- State or USEPA regulatory guidance which specifies RBSLs and describes acceptable analytical MDLs.

- Air Force guidance such as the AFCEE *Quality Assurance Program Plan, March 1998*
- AFCEE *Technical Protocol for Implementing Intrinsic Remediation(Natural Attenuation) with Long-Term Monitoring for Dissolved-Phase Fuel Contamination.*
- Analytical laboratories which must comply with the latest version of USEPA *Test Methods of Evaluating Solid Waste Physical/Chemical Methods SW846* (Current 6/97, 3rd Edition), which provides detailed information on USEPA-approved analytical procedures.
- Other USEPA documents such as OSWER Directive 9242.6-08 (USEPA, 1993b), which provides practical guidance on establishing DQOs.
- Engineers/scientists who will require specific data to evaluate risk, natural attenuation, or source reduction technologies.
- Geologists/hydrogeologists who must complete field sampling

The work plan should include a sampling and analysis plan specifying site investigation and sampling procedures that will ensure proper QA/QC during data collection. A complete discussion of specific data quality requirements is beyond the scope of this document. Appendix G provides several references that describe data quality and QA/QC issues in greater detail.

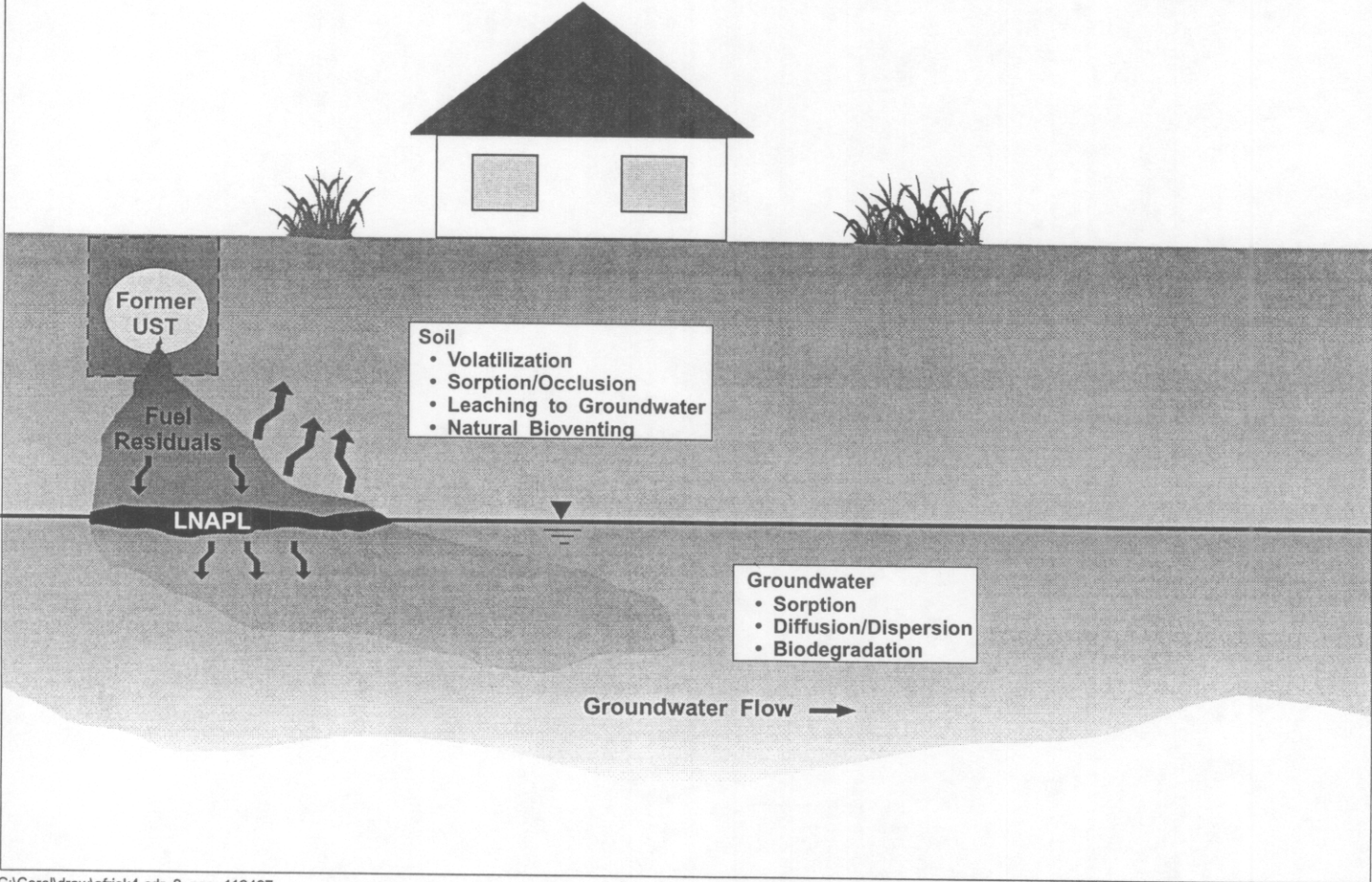
B.5.4 Planning for a Chemical Fate and Transport Assessment

Table B.1 includes site characterization requirements intended to support both streamlined and a more comprehensive chemical fate and transport assessment. Key parameters for qualitative and quantitative estimates of natural biodegradation processes in the soil and groundwater should also be collected at all petroleum-contaminated sites. A brief description of how these data are used in fate and transport evaluation process follows. Figure B.3 illustrates many of the important fate and transport phenomenon that may exist at a typical fuel contamination site. Appendix C provides additional guidance on how to complete simple fate and transport estimates.

B.5.4.1 Soil Gas Surface-Flux and Confined-Space Monitoring

The volatile components of gasoline and JP-4 often create a significant source of hydrocarbon vapors that can move to the ground surface as a result of barometric pressure changes and convective/diffusive processes. When the source of fuel contamination is located beneath or near buildings or underground utility corridors, these vapors also can enter these confined spaces at concentrations which pose either an inhalation risk or, in extreme cases, an explosive hazard. Although empirical formulas are available to estimate soil gas emissions based on soil concentrations, actual measurements of VOC concentrations in soil gas and at the ground surface are far more useful in the risk evaluation process. Three methods of sampling are generally used:

FIGURE B.3
SIGNIFICANT CHEMICAL FATE AND TRANSPORT MECHANISMS



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- To determine the potential soil gas concentrations that may impact the inhalation pathway, temporary soil gas probes can be driven into shallow soils in the source area, and a gas sample can be extracted for laboratory analysis of the BTEX compounds. *Addendum One to the AFCEE Test Plan and Technical Protocol for Field Treatability Testing For Bioventing- Using Soil Gas Surveys to Determine Bioventing Feasibility* describes these soil gas sampling techniques.
- To determine the potential exposure of site workers to volatile contaminants in the breathing zone, flux chambers are placed on the site surface to monitor the release of volatile hydrocarbon vapors from the subsurface. Several flux samples must be collected in potential exposure areas to determine the average mass of contaminants which are being released each day. A flux sampling method described by Dupont (1988) is recommended.
- To determine the potential accumulation of volatile contaminants in enclosed spaces such as buildings and underground utilities, sampling of ambient air from these structures is recommended. Field instruments (e.g., a photoionization detector) can be used for screening such areas, but any VOC detection that exceeds 5 ppmv should be verified by laboratory analysis. The 5-ppmv concentration represents the 8-hour Occupational Safety and Health Administration (OSHA) permissible exposure limit for benzene, which provides a worst-case screening criterion. The Air Force Occupational, Safety, and Health Standards 161 and 48-8 provide guidance on conducting ambient air monitoring. The base bioenvironmental engineer is trained in these techniques.

B.5.4.2 Contaminants Leaching from Soil and Free Product into Groundwater

A controlling factor in the remediation of groundwater contamination is often the rate at which contaminants are partitioning from contaminated soil or free product in the source area. When planning a site characterization, a better definition of the relationship between source contaminants and the dissolved plume should be a primary objective. Several analyses such as total organic carbon (TOC) content of uncontaminated soils, clay fraction, and the distribution of source area contaminants in relation to the groundwater will help to estimate the partitioning process. Although the quantity of free-phase product on any site is difficult to estimate, the use of low-cost soil coring devices can provide more sampling locations and better define the oily-phase product present in the soil. The analysis of free product samples for the mass fraction of BTEX or polynuclear aromatic hydrocarbon (PAH) compounds is essential for estimating the future contribution of free product to the dissolved plume. Appendix C provides additional information on methods for estimating contaminant partitioning.

B.5.4.3 Natural Chemical Attenuation of Fuel Hydrocarbons

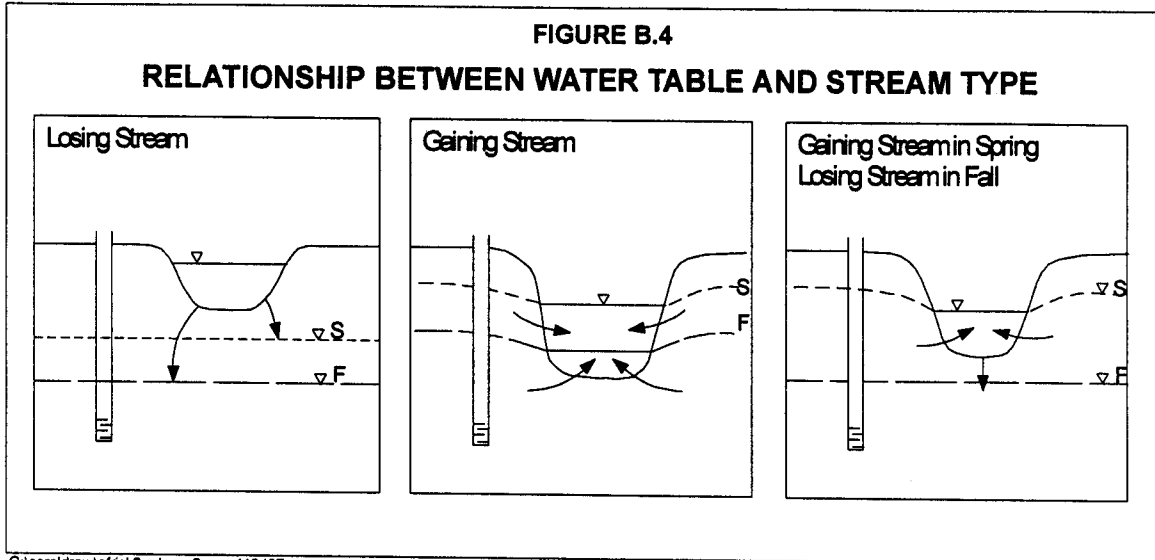
Recent advances in the science and documentation of natural chemical attenuation processes at fuel-contaminated sites have clearly shown that natural biodegradation is the remedy of choice for dissolved hydrocarbon plumes. To date, AFCEE has completed over 50 separate studies of large petroleum release sites, and in almost every case, natural biodegradation alone has been or will be sufficient to remove dissolved BTEX from the groundwater before human or ecological receptors are impacted. The

AFCEE *Technical Protocol for Implementing Intrinsic Remediation (Natural Attenuation) with Long-Term Monitoring for Dissolved-Phase Fuel Contamination* was developed to provide specific guidance on how to sample and analyze for a variety of geochemical indicators that can be used to document natural biodegradation and other attenuation processes. This protocol is a critical component of any risk-based remediation work plan because natural attenuation is often the most effective risk-reduction process operating at fuel-contaminated sites. Table B.1 includes a list of the geochemical analytes recommended by this protocol. Appendix B.7 describes how to best use existing and new monitoring wells to gather data for natural attenuation.

At some sites, the source of hydrocarbon contamination in the soil may be significantly reduced by natural biodegradation processes. During the recently completed AFCEE bioventing initiative, nearly 15 percent of the sites screened for pilot testing were found to have sufficient oxygen levels to promote natural bioventing (AFCEE, 1996). In fact, the risk-driving BTEX compounds were almost entirely degraded in soils that were undergoing natural aerobic biodegradation. Sites with shallow contamination in sandy soils often were receiving enough oxygen through diffusion or barometrically driven air exchanges to sustain continuous aerobic biodegradation. *Addendum One to the AFCEE Test Plan and Technical Protocol for Field Treatability Testing For Bioventing- Using Soil Gas Surveys to Determine Bioventing Feasibility* provides details on how to conduct a soil gas survey to determine the distribution of oxygen, carbon dioxide and hydrocarbon vapors at a site, and how these data can be used to document natural bioventing or to design a mechanical bioventing system. Soil gas analysis for oxygen and carbon dioxide (Table B.1) is intended for this purpose.

B.5.4.4 Assessing Potential Surface Water Impacts

Site-specific data will be required when site contamination has or could impact surface waters. In many states, the definition of surface waters can include stormwater drainage ditches if they eventually discharge to a stream, lake, or wetland. It is important to establish the relationship between shallow groundwater and any surface water that is possibly downgradient of the site. Figure B.4 illustrates three possible interactions between surface water and shallow groundwater. Knowledge of seasonal groundwater elevation and local stream flow changes is very important to an accurate assessment of how contamination could impact aquatic receptors. The fate and transport appendix of Table B.1 includes the data required to estimate the impact of fuel hydrocarbons on a surface water body. Sampling and analysis for fuel hydrocarbons both upstream and downstream from the plume discharge point is required to determine the contribution of the plume to surface water quality problems. An additional sampling point 100 to 200 feet downstream is useful for determining how natural attenuation is reducing the impact of site contaminants on any downstream human or ecological receptors. Stream flow or volume estimates are required to determine dilution and volatilization effects. Ecological characterization of local plant and aquatic life is discussed in Appendix B.8.



B.5.5 Planning for Pilot Testing of Source Reduction Technologies

The work plan should also integrate site investigation activities with opportunities to conduct simple pilot tests of source reduction technologies that are likely to be applied at the site. For example, soil borings in contaminated soil can be completed as venting wells and vapor monitoring points so that a short-term bioventing test can be completed during the field mobilization for site characterization. *In situ* respiration testing and air permeability testing often can be completed in 4 days or less and can be conducted concurrently with other site characterization activities. The *AFCEE Test Plan and Technical Protocol for a Field Treatability Test for Bioventing* contains guidance on how to compete these simple tests and make maximum use of soil gas surveys, monitoring wells and soil borings. If free product exists at the site, bail-down tests can be completed using existing monitoring wells, and the results can be used to estimate the feasibility of recovering free product using passive or active recovery systems. Appendix B.7 also describes tests that can be completed during site characterization to determine aquifer hydraulic conductivity and the feasibility of pump-and-treat technologies.

B.6 CHARACTERIZING THE CHEMICAL SOURCE

Objectives of any risk-based site characterization include locating areas where COPCs are concentrated and determining the short- and long-term potential of such chemicals to pose an unacceptable risk to potential receptors. In most cases, the source of contamination is known to be a former UST or leaking pipeline location. At sites with complex piping systems, it is often difficult to pinpoint the exact source of contamination, and at some active sites, small leaks will continue to add fuel to the subsurface even while site remediation is underway. Because large continuing leaks are not acceptable, periodic leak testing of pipelines and tanks should be required at all active fueling sites. Small leaks (<1 gpd) often are impossible to detect, and at many sites rates of natural biodegradation may be fast enough to assimilate these small, continuous fuel releases. However, the "continuing source" assumption is not likely to be an acceptable component of a risk-based corrective action.

B.6.1 Locating and Estimating Free Product Impacts

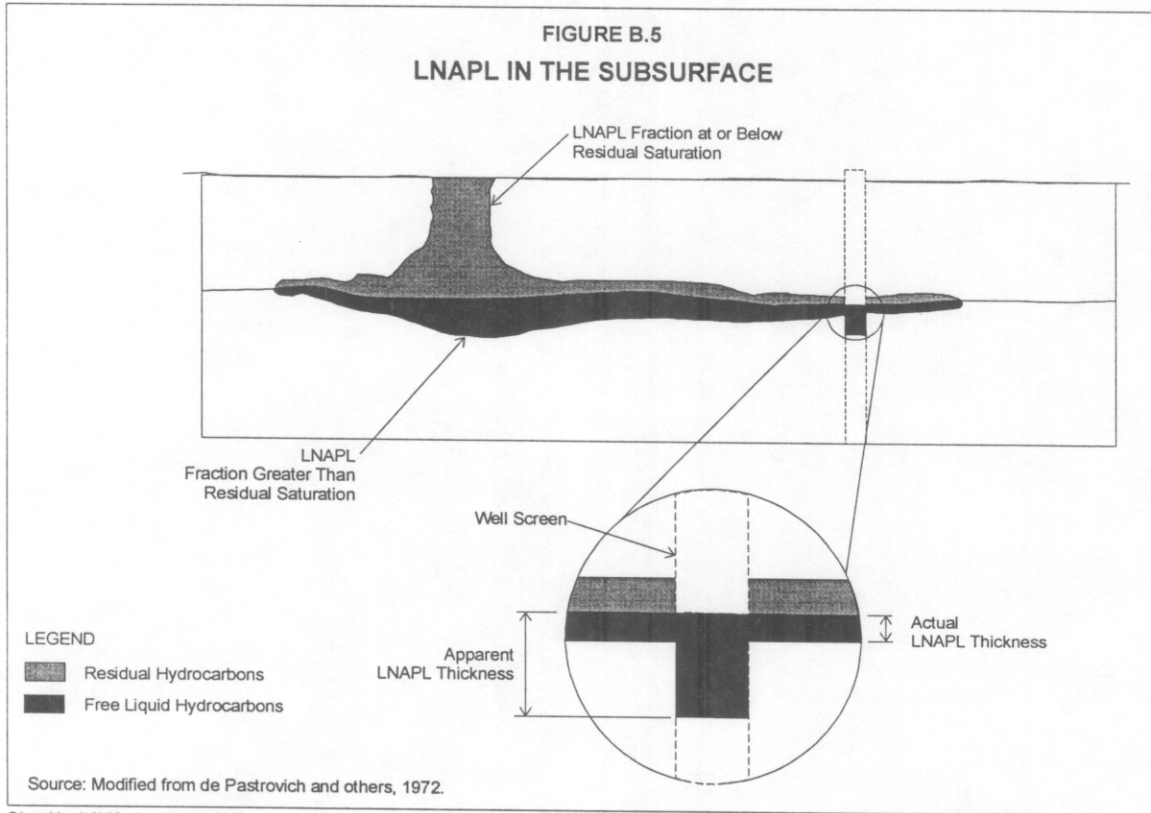
Estimating the extent of free product on any site and its long-term impact on soil, soil gas, and groundwater remains one of the most difficult tasks in the site remediation process. Because free product represents a concentrated mass of COPCs at most sites, assumptions regarding its volume, current location, natural weathering, or the success of engineered removal will significantly influence estimates of total remediation time. At most sites with leaking tanks or pipelines the date of release is unknown. However, if the dates of major spill events are known, this information can greatly improve the accuracy of any model used to predict fuel weathering rates. Adequate free product characterization is critical in order to reduce the uncertainty of natural attenuation predictions.

When a fuel release occurs in the soil, the fuel exists as a non-aqueous-phase liquid (NAPL). Light NAPLs (LNAPLs) are fluids that are lighter than water and do not mix well with water. With the exception some chlorinated solvents such as trichloroethene, most petroleum products used by the Air Force are LNAPLs. Figure B.5 is a simplistic illustration of LNAPL movement in the subsurface. When released, LNAPL migrates downward through pore spaces in the soil that are not filled with water. Each soil type has a certain capacity to retain the LNAPL in its pore spaces; this capacity is known as residual saturation. If the volume of fuel released is small, the entire fuel volume may be adsorbed or trapped in the unsaturated soil (soil above the groundwater) without exceeding the residual saturation. If the volume of fuel released is large, the residual saturation may be exceeded, and the LNAPL will continue to migrate downward until it encounters a less permeable layer or the groundwater. In either case, the LNAPL will generally form a lens of "free product" on top of the groundwater or an impermeable soil layer. Free product, or mobile LNAPL, is defined as that LNAPL that will flow from the soil into a monitoring well once the residual saturation of the soil has been exceeded. LNAPL can be distributed throughout the subsurface in several phases, including soil residuals, saturated soils, free product, soil vapor, and dissolved in the groundwater.

To more accurately determine the extent and volume of LNAPL contamination at a site, a combination of soil gas, soil sampling and free product thickness measurements are recommended. Soil gas and soil sampling methods are covered in Appendix B.6.2.

Figure B.5 also shows the typical relationship between LNAPL thickness measured in a monitoring well and the actual thickness that would be present at the capillary fringe. As shown in the figure, the accumulation measured in a well may be several times greater than the actual thickness. The difference between apparent and actual thickness is most pronounced in fine-grained soils. To date, no simple model has been developed to correlate these two thickness, although it has been the subject of much research. In light of this fact, the Air Force now recommends that, whenever LNAPL is anticipated at a site, continuous split-spoon soil samples be collected near the suspected source of the fuel release. As a minimum, samples should be collected in the soil intervals that correspond with the record high and low groundwater elevations at the site. The extracted soil core should be visually checked for an oily-phase layer. An ultraviolet light can be used to check for a fluorescent layer that indicates a high concentration of fuel hydrocarbons. The observed (actual) thickness of this LNAPL layer should be compared with the thickness of LNAPL that has accumulated in

monitoring wells to better estimate the actual volume of the LNAPL lens. It is important to remember that a relatively small fraction of the LNAPL mass at any site can be recovered as "free product". Appendix E describes product "bail-down" procedures for estimating if the LNAPL is recoverable.



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In addition to estimating the volume of LNAPL, it is equally important to determine through chemical analysis the mass of chemicals of potential concern (COPCs) that remain within this product. The mass fraction of BTEX and other COPCs in the fuel will decrease over time due to natural weathering processes such as dissolution into groundwater and volatilization. The current mass of COPCs will determine how long the product will act as a source of groundwater or soil vapor contamination. Table B.1 lists the recommended analyses for product samples.

In summary, the portion of the site investigation work plan pertaining to free product characterization should focus on three objectives:

1. The use of soil cores taken from the capillary fringe to determine product thickness. Whenever possible, a direct-push soil sampling device or cone penetrometer should be used to collect a greater number of soil samples from the capillary fringe. Product thickness estimates based on groundwater monitoring wells should be avoided due to seasonal water level effects and the significant discrepancies between observed and actual product thickness. Cohen and Mercer (1993) provide a more detailed discussion of free product characterization methods.

2. The collection of at least two free product samples for analysis of the COPC mass fraction remaining in the fuel. This will provide important information on the long-term contribution of contaminant mass to the groundwater and allow for more accurate modeling of the potential biodegradation of the plume.
3. A short-term product recovery test should be performed to determine if significant product can be recovered from the formation. Simple bail-down tests are recommended at wells containing more than an inch of free product. Procedures for completing baildown tests are discussed in the *AFCEE Test Plan and Technical Protocol for Bioslurping*.

B.6.2 Soil Gas Surveys

On sites where the location of an underground leak is unknown, a preliminary soil gas survey can be extremely helpful in focusing soil sampling efforts in the "hot spots", and also can provide valuable information on the bioventing potential of the site. As discussed in Appendix B.5.4.1, soil gas surveys also are useful in determining the potential risk from soil vapors, particularly when contaminated soil is beneath occupied buildings.

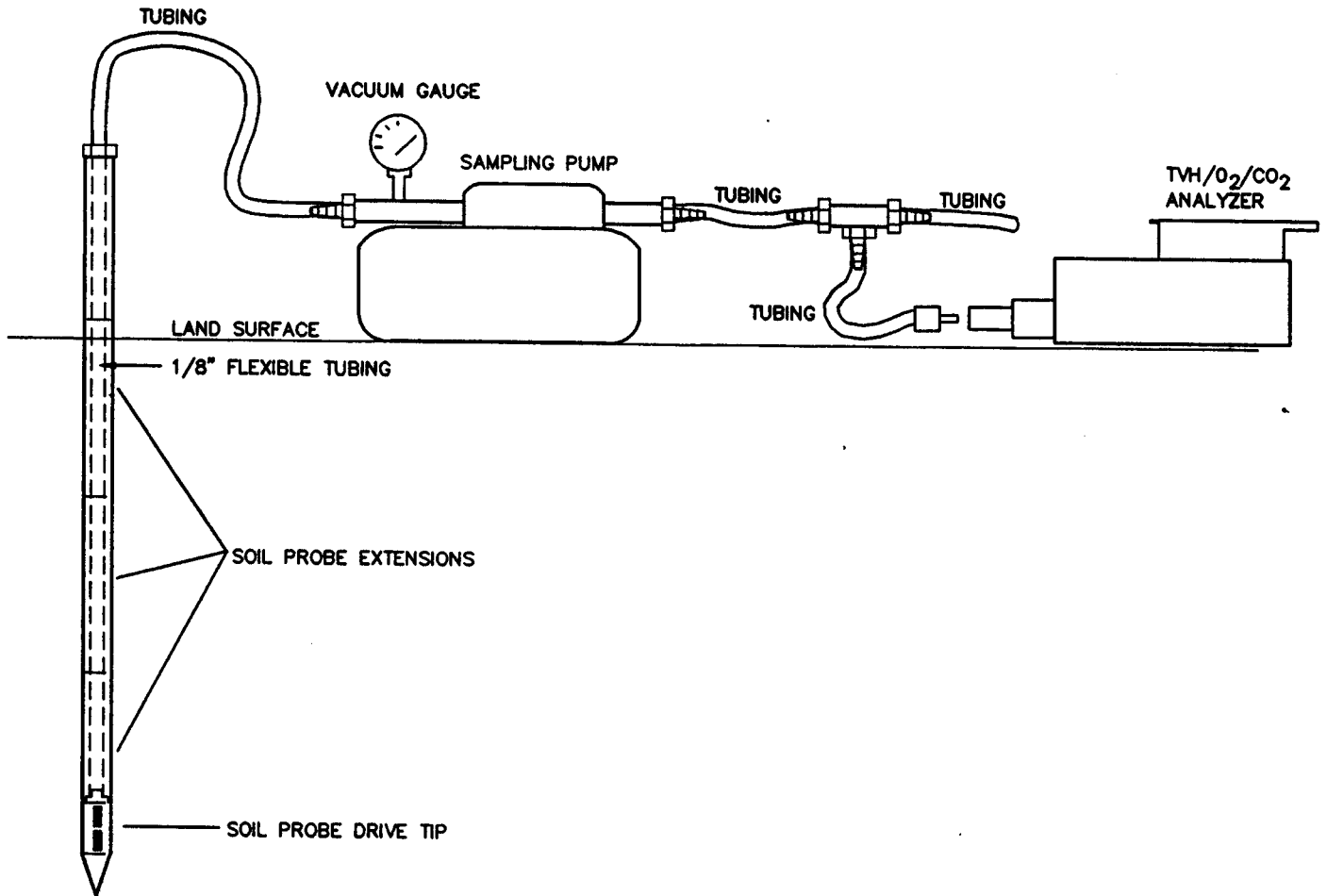
Figure B.6 illustrates a basic soil gas survey system that can be used on a small or shallow site. Soil gas points can often be hand-driven using a drop hammer or an electric hammer attachment to drive the probes. At sandy sites, this technique has been used to depths of over 20 feet; however, for silt or clay soils or for larger sites, a hydraulic-drive mounted to a van or pickup truck is the preferred method of driving the metal soil gas points.

A survey grid is normally laid out, and soil gas is analyzed using a field hydrocarbon meter or a portable gas chromatograph. Oxygen and carbon dioxide analysis is also useful to determine if biological activity has consumed all available oxygen and to assess the potential for natural or mechanically enhanced bioventing. Low oxygen levels generally correspond to areas of significant residual LNAPL contamination and also indicate that natural bacteria are present but are unable to continue to aerobically degrade the hydrocarbons without additional oxygen. A complete description of how to complete a soil gas survey is found in *Addendum One to the AFCEE Test Plan and Technical Protocol for Field Treatability Testing For Bioventing- Using Soil Gas Surveys to Determine Bioventing Feasibility*, referenced in Appendix G.

B.6.3 Soil Sampling

At most fuel-contaminated sites, the majority of the hydrocarbon mass is adsorbed or occluded in the soil. These fuel residuals acts as a long-term source of contamination to groundwater or soil gas. Too often, the focus of remediation has been on groundwater decontamination because of its "potential" use as drinking water, and little attention has been given to current risk from highly contaminated soils. This risk may be particularly important when excavations are planned in contaminated areas. The delineation of both the volume and the concentration of fuel contamination in soil is a critical component of the risk-based approach.

FIGURE B.6
DIAGRAM OF SOIL GAS PROBE AND SAMPLING SYSTEM



B.6.3.1 Low-Cost Soil Sampling Techniques

Whenever possible, a soil gas survey should be used to help focus the soil sampling effort. At small UST sites, the first soil sample should be collected as close to the expected center of contamination as possible, with an additional sample collected from each side of the anticipated source to determine if the fuel release has migrated in any one direction. At a larger site, locating sampling points on a grid is often the most cost-effective way to begin the investigation. As contaminated areas are encountered, the sampling locations can be focused in a portion of the grid.

The use of hydraulically driven soil sampling probes is recommended to collect soil samples on sites with contamination within 30 feet of the surface. If the soils are predominantly clay or contain cobbles, these probes will be limited in their depth of penetration. Conversely, direct-push probes have been used to depths of over 100 feet in some sandy soils. Most probes systems have accessories that allow collection of a variety of different soil cores as well as soil gas and groundwater samples. Larger cone penetrometer testing (CPT) systems can penetrate a greater variety of soils, and have sensors embedded in the probes to measure penetration resistance, soil vapors, and the fluorescence of an LNAPL layer. At sites where bioventing or soil vapor extraction are the likely soil remediation methods, permanent soil gas collection probes also can be placed using these systems. One significant advantage of push probes is that they do not generate drill cuttings and the associated costs of soil handling, sampling and disposal, which are major issue at some sites.

In deeper or more difficult soils, the use of hollow-stem augers and a continuous split-spoon sampling device is the recommended sample collection method. Continuous coring allows for screening of the soils both for fuel staining and for vapor production, which is often measured with a handheld vapor analyzer. One additional advantage of the hollow-stem auger method is that it can also be used to install permanent 2-inch or 4-inch soil venting wells or groundwater monitoring wells. Perhaps the most cost-effective technology combination is the use of direct push soil probes for determining the source area and general extent of contamination, and the use of more expensive hollow-stem augering for selected permanent wells. *Never abandon and grout a soil boring if it can be used in the soil or groundwater remediation or monitoring system.* Soil borings in contaminated soil should be completed as venting wells or permanent soil vapor monitoring points. Borings extending below the water table should be completed as monitoring wells or multi-depth monitoring points. Additional information on maximizing the future use of site investigation borings is included in the AFCEE Bioventing Protocol (Hinchee *et al.*, 1992).

B.6.4 Investigation-Derived Waste (IDW)

Field investigations at petroleum-contaminated sites will generate wastes such as drill cuttings, well development and purge water, decontamination rinse water, and personnel protective clothing items. Regulatory requirements for labeling, sampling, handling and disposing of these items vary significantly from state to state. Before beginning the field investigation, IDW management procedures should be clearly described in the investigation work plan or sampling and analysis plan. Every effort should be made to minimize the volume of IDW generated including segregation of

clean drill cuttings from fuel-contaminated cuttings, segregation of clean background well water from contaminated well water, and the use of CPT or direct-push technologies to eliminate drill cuttings altogether. To reduce the cost of site investigations, many states now allow the spreading of soil cuttings and well water on the site if they contain only fuel contaminants. At sites containing heavy metals or other non-petroleum contamination, the wastes are generally placed in 55-gallon barrels, sampled, sealed, labeled, and placed in an on-base RCRA storage facility until they are picked up by a licensed hazardous waste disposal contractor.

B.7 CHARACTERIZING DISSOLVED CHEMICAL CONTAMINATION

This appendix describes the primary elements of a successful groundwater investigation at fuel-contaminated sites. Although the type of monitoring wells installed and the equipment used to install and sample the wells will vary based on site-specific conditions, there are general requirements and procedures that apply to all sites.

B.7.1 Monitoring Locations

Optimization of monitoring well locations will ensure that useful data are collected and the cost of site investigation is minimized. Monitoring wells serve many purposes, and optimum location selection is often driven by several objectives. A good CSM (Appendix B.3) will identify the probable source of contamination, the probable groundwater flow direction, and any downgradient receptors that could be impacted by contaminated groundwater. One objective of monitoring well placement is to place at least one well in the suspected source area and to place a second well between the source and the potential downgradient receptor exposure point. A second objective in well placement is the need to establish the hydraulic conductivity and gradients of the affected aquifer. An upgradient well and at least one additional downgradient well are required to establish these parameters. An upgradient well also is needed to establish background concentrations of DO and other electron acceptors used to estimate natural biodegradation potential. Figure B.7 illustrates the basic well locations that satisfy the first two objectives.

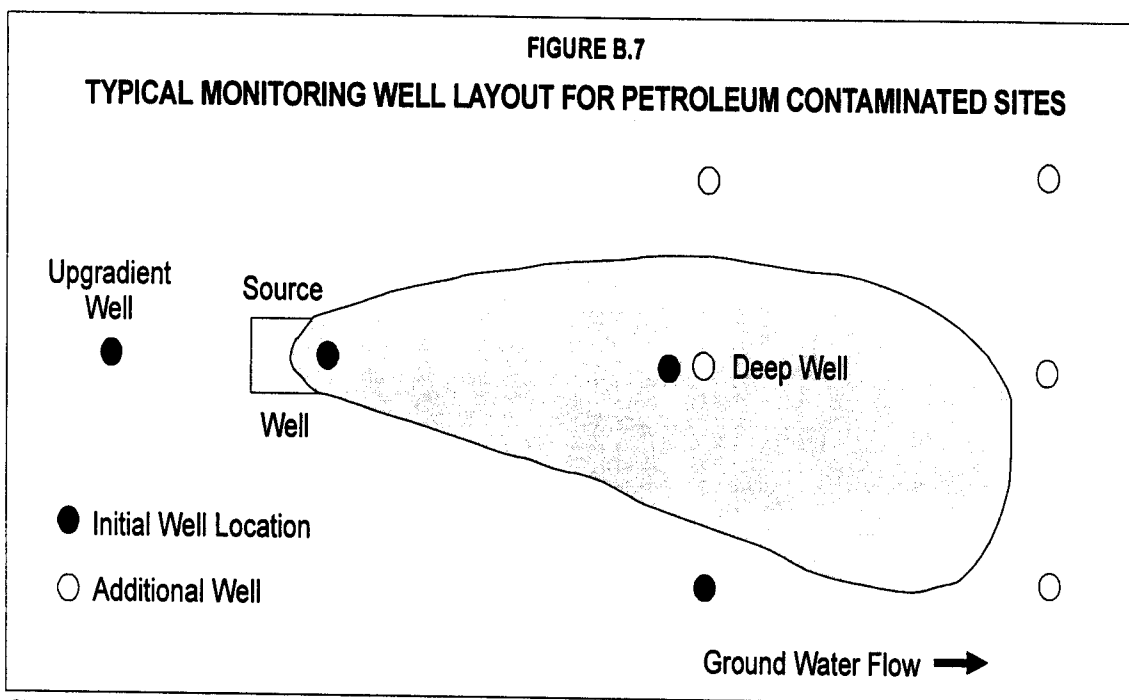
Once a source area has been located and the general groundwater direction determined, additional wells will be required to determine the maximum forward and lateral migration of the plume. Figure B.7 shows the positions of additional wells that can be used to "bound" the groundwater plume. The total number of wells installed at each site will vary with the size of the source area and the length of the resultant plume.

B.7.2 Well Installation

Typical installations for permanent wells and temporary well points are described in this appendix. Both of these methods have distinct advantages and disadvantages that are important to understand before planning a groundwater investigation.

B.7.2.1 Permanent Well Completions

Permanent monitoring wells are generally completed in boreholes created by a variety of different drilling techniques that are selected based on the soil type and desired borehole depth of drilling. A full description of well placement techniques and



well completion instructions can be found in Appendix B of the National Water Well Association (1989) *Handbook on the Design and Installation of Monitoring Wells*. Figure B.8 illustrates a typical monitoring well completion for a fuel-contaminated site.

Because the compounds that make up fuels are less dense than water, dissolved contamination tends to remain in the upper 10 feet of most aquifers, with the highest concentrations just below the capillary fringe. To accurately determine the extent of dissolved contamination, well screens are normally completed in the upper 5 feet of the aquifer. The use of a 10-foot screened interval with 5 feet of screen below the average groundwater elevation, and 5 feet of screen above the average water mark (Figure B.8) will provide a multiple-use well that can be used for groundwater sampling, free product measurement, and soil vapor monitoring. At smaller sites, this multi-use well design has also been used to inject air for bioventing.

Because regulatory agencies are often concerned about downward migration of contaminants toward deeper aquifers, most site investigations should include at least one well completed into the deeper portion of the upper aquifer. These wells are normally completed with 5 feet of screen placed near the bottom of the upper aquifer. Special care is required during installation to prevent cross-contamination between the contaminated capillary fringe and the deeper aquifer. Special drilling techniques are required to seal off the upper zone of contamination from the deeper aquifer. Few sites have a downward hydraulic gradient that will transport dissolved contaminants more than 20 feet below the groundwater surface. Cross-contamination is a far more common cause of dissolved contaminant detections in deep wells. One way to reduce the potential for cross-contamination is to drill deep wells slightly downgradient from the source area. Never drill a deep well through an LNAPL layer.

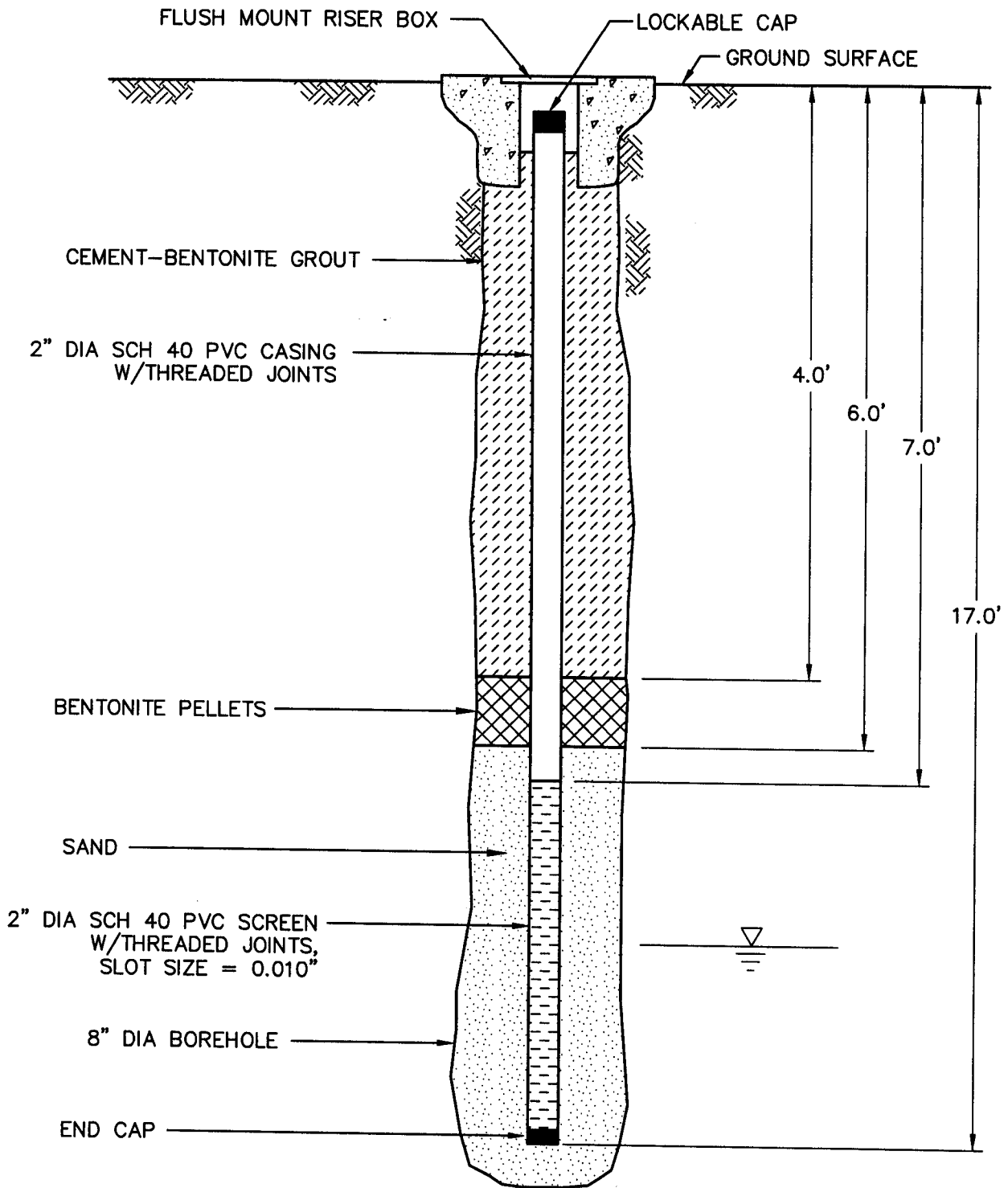


FIGURE B.8
TYPICAL
MONITORING WELL
CONSTRUCTION

B.7.2.2 Low-Cost Well Point Completions

Recent advances in CPT and other direct push technologies has resulted in more widespread acceptance of both permanent and temporary well points for groundwater sampling. Groundwater monitoring points differ from monitoring wells in that the soil "boring" is created using a CPT or push rod. Additional information on the use and installation of well points is provided in the *AFCEE Technical Protocol for Implementing Intrinsic Remediation (Natural Attenuation) with Long-Term Monitoring for Dissolved-Phase Fuel Contamination*. Most well points are constructed of 0.5- to 1-inch-diameter polyvinyl chloride (PVC) with screened intervals of 2 to 5 feet. Because of the small diameter of these holes (<2 inches), there is little or no annular space (or sand pack) between the well screen and the soil formation. Without the filtering effect of the sand pack, well points will generally produce less water and are more susceptible to clogging due to silt accumulation. The lack of a good bentonite seal also can lead to cross-contamination, as contaminants may flow down the small but open annular space. Because of these disadvantages, permanent well points are most appropriate for shallow unconfined aquifers that are predominantly sand. Sandy aquifers tend to collapse into and rapidly fill the annular space preventing significant vertical flow. Sampling equipment such as mini-bailers and peristaltic pumps are needed for sample acquisition from small diameter wells. Figure B.9 shows a typical well point installation.

Several manufacturers such as Hydropunch™, Stratoprobe™, and Geoprobe™ have developed sophisticated water sampling probes that can be driven into the aquifer to collect a one-time groundwater sample or left in the formation for long-term sample retrieval. These tools are excellent for low-cost field efforts where the goal of the investigation is plume delineation and a semi-quantitative chemical analysis. At shallow sites it is possible to collect samples from as many as 15 locations in a single day. When used in conjunction with a field gas chromatograph, these sampling techniques provide for rapid plume mapping, and often are used to optimize the location of more expensive permanent wells using standard drilling techniques. One disadvantage of groundwater probes is that sampling results from these systems are often questioned by regulatory agencies who view them as semi-quantitative and not reproducible.

B.7.3 Groundwater Sampling and Analysis

There is ample guidance on proper groundwater sampling techniques (e.g., AFCEE RI/FS Statement of Work Handbook, AFCEE Technical Protocol for Implementing Intrinsic Remediation (Natural Attenuation) with Long-Term Monitoring for Dissolved-Phase Fuel Contamination). The techniques detailed in the available guidance are summarized in this appendix. Before undertaking any sampling and analysis activities, a complete sampling and analysis plan (SAP) should be developed and reviewed by a qualified Air Force site investigation specialist. The SAP should include detailed procedures for sample acquisition, sample handling and preservation, equipment decontamination, and QA steps such as the collection of field duplicates, equipment rinsate samples, and field blanks. Early identification of Air Force and regulatory sampling and analysis DQOs will ensure that useful data are available for risk analysis and fate and transport studies.

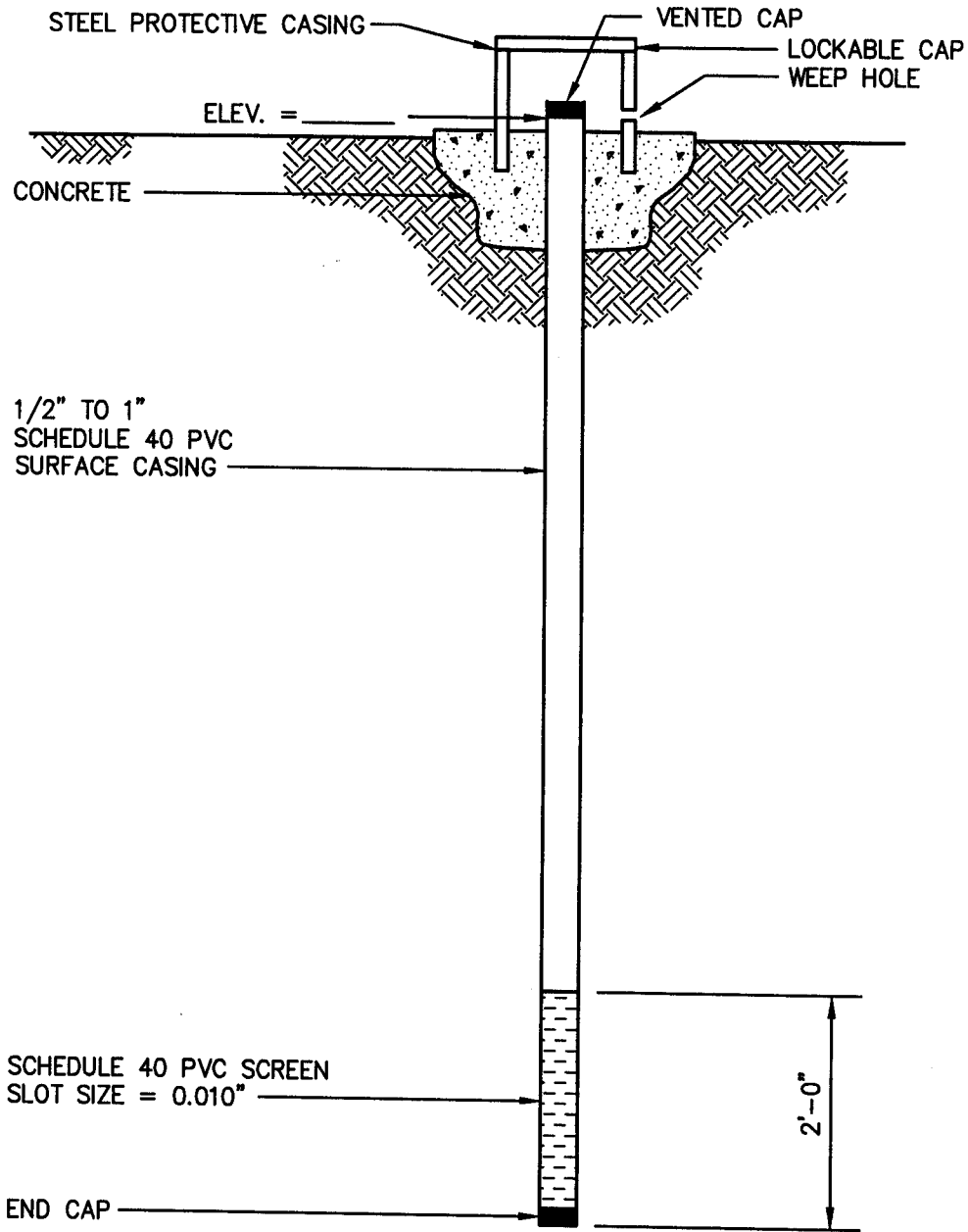


FIGURE B.9
TYPICAL
WELL POINT
COMPLETION

B.7.3.1 Well Development and Water Level Sampling

Prior to collecting groundwater information from any well or well point, the well should be developed to remove sediment from inside the well casing and to remove drill cuttings or drilling fluids from the sand pack near the well screen. For larger well installations or installations in clay soils, wells should be allowed to equilibrate for several days before sampling can begin. For shallow wells in sandy soils, often only a few hours are required before sampling can begin.

The first and last measurement taken during a groundwater sampling event is the groundwater elevation at each well. Electronic water level or oil/water interface probes with graduated measuring tapes are commonly used to for this measurement. The distance between the groundwater surface and a specific point on the well casing normally is recorded in the field book. The exact elevation of the well casing above mean sea level is then determined by a professional surveyor to determine the gradient or flow direction of site groundwater.

When small diameter (<1 inch) well points and groundwater probes are used, an alternate water level measurement method is needed. A monometer or pressure gauge is connected to a length of 0.25-inch inside-diameter (ID) high-density polyethylene (HDPE) tubing, which is inserted down the well point. When the tubing reaches the water table a pressure is detected, the tubing is marked at the top of the casing, removed from the well and the distance from the mark to the bottom of the tubing is measured to determine the groundwater depth.

B.7.3.2 Free Product Thickness Measurements

If free product is suspected at the site, there are several methods available for measuring free product thickness. For large-diameter wells, an oil/water interface probe provides the most accurate measurement of product thickness and depth to groundwater. For smaller well points (<1-inch ID) mini-bailers and special fuel-sensitive tapes are available for estimating product thickness. Recall from Appendix B.6.1 that the apparent product thickness in a monitoring well is generally greater than the actual free product thickness in the formation. Product thickness will also vary significantly with groundwater elevation changes. Thicker product accumulations in wells are normally associated with periods of low groundwater elevation. Verification of product thickness with a clear, disposal bailer is recommended to check electronic indicators. A bailer also should be used to collect at least one product sample from each source area. Table B.1 recommends specific analyses for different types of suspected fuel.

B.7.3.3 Well Purging and Sample Acquisition

Based on the water level measurement for each well and the total well depth, the volume of water in each well can be calculated. Prior to sample acquisition, the well or well point should be purged of at least three well volumes. During the purging procedure, groundwater temperature and pH are monitored to determine when the well has reached equilibrium with the groundwater. To prevent cross-contamination, a dedicated bailer or a peristaltic pump with dedicated polyethylene tubing should be used for well purging. Bailers are preferred for 2-inch monitoring wells, and peristaltic

pumps are often needed for small-diameter well points or probes. Purge water is generally placed in a 55-gallon drum, and after sampling can often be disposed of at the site or in a sanitary sewer.

The method of collecting the groundwater sample will vary with the diameter of the well, depth to groundwater, and volume of sample to be collected. The use of dedicated Teflon® bailers is recommended for permanent wells that will require regular sampling. Mini-bailers as small as 7/16-inch outside diameter (OD) are available for sampling smaller well points. Bailers are simple to use and are generally acceptable for the collection of samples for VOC analysis. An alternate method of sample acquisition that has distinct advantages for measuring dissolved oxygen is the use of a peristaltic pump. The pump is connected to a dedicated length of Teflon®-lined tubing which is lowered several feet below the groundwater surface. The groundwater is pumped to the surface with minimum exposure to the atmosphere which provides for accurate DO measurements. One disadvantage of this method is that it is limited to groundwater depths of 20 to 25 feet due to the limitations of suction lift. When using the peristaltic pump, care must be taken to ensure that air bubbles are not forming in the influent to the pump. Air bubbles may indicate that the suction lift has been exceeded, and will result in distorted DO readings and volatilization of VOCs from the water sample.

B.7.3.4 Field Analyses

Many important groundwater parameters, including the geochemical indicators of natural biodegradation, can be measured in the field and can provide real-time feedback on the locations of the source area and plume. Table B.1 lists the recommended field measurements for petroleum-contaminated sites, including temperature, pH, redox potential, and DO, which are measured with field instruments, and alkalinity, nitrate/nitrite, sulfate, ferrous iron, and manganese, which are measured using colorimetric Hach® kit analysis. A complete discussion of the sampling methods and the use of each of these analysis is included in the *AFCEE Technical Protocol for Implementing Intrinsic Remediation (Natural Attenuation) with Long-Term Monitoring for Dissolved-Phase Fuel Contamination*.

B.7.3.5 Sample Processing

Close coordination with the receiving laboratory will help ensure that each sample is properly handled and placed in the proper sample container. Most laboratories now supply detailed instructions for sample handling and shipment and provide all sample containers, complete with required sample preservatives. Unless other instructions are given by the laboratory, sample containers should be completely filled so that no air space remains in the container. This is critical for samples that will be analyzed for VOCs. Sample labels should be completed, and a chain-of-custody form should be completed for each sample shipment. A separate field log also should be kept to track when and where each sample was taken. Samples are normally shipped in impact-resistant coolers which contain cooling media to maintain a shipping temperature of approximately 4 degrees Celsius.

B.7.4 Aquifer Characterization

An adequate understanding of groundwater flow is essential for proper site characterization and for predicting contaminant fate and transport mechanisms. Two of the most important factors in determining groundwater flow are hydraulic conductivity (K), which defines the ability of an aquifer to transmit water, and hydraulic gradient, which determines the direction of flow through the aquifer.

B.7.4.1 Hydraulic Conductivity

Hydraulic conductivity is an important factor in determining how far and how fast a contaminant will be carried away from the source area and toward a potential receptor exposure point. The fate and transport estimates provided by models such as BIOPLUME are highly dependent upon the assumed hydraulic conductivity of the affected aquifer. The importance of a good estimate of hydraulic conductivity based on field measurements cannot be overstated.

There are two primary methods of estimating hydraulic conductivity, and both should be used if at all possible. Slug tests are by far the simplest to perform and can be completed on numerous wells simultaneously. Slug tests also are favored because no water is produced. A slug test consists of adding (falling head test) or removing (rising head test) water from a well and measuring the rate at which the water level recovers to its pretest elevation. Slug tests should be performed on all wells present at the site to provide the best average estimate of hydraulic conductivity. This is especially important at sites with considerable heterogeneity of the aquifer matrix across the site.

Another method for estimating hydraulic conductivity is a pumping test. A pumping test is performed by placing a submersible pump in a well and continuously pumping the well at a constant rate while measuring the drawdown in the well and in nearby observation wells. One advantage of this test is that it allows for a larger volume of the aquifer to be tested rather than the limited area that responds to a slug test. The obvious disadvantage of this test is that large volumes of water must be treated and disposed of. One way of reducing the cost of a pump test is to use a clean well located in similar geology but several hundred feet away from the site. This may eliminate the need for treatment and allow the water to be discharged to a drainage ditch or storm sewer. A detailed description of hydraulic conductivity test procedures is included in the *AFCEE Technical Protocol for Implementing Intrinsic Remediation (Natural Attenuation) with Long-Term Monitoring for Dissolved-Phase Fuel Contamination*.

B.7.4.2 Hydraulic Gradient

To determine the direction of groundwater flow and the horizontal hydraulic gradient, water level measurements are taken from all available wells within a short time interval. It is equally important that the location and elevation of each well be surveyed so that the groundwater depth at each well can be corrected to a fixed datum. The top of each well casing should be surveyed to the nearest 0.01 foot. With this information, an accurate map of the groundwater surface can be created to determine flow direction and the average change in groundwater elevation over distance (hydraulic gradient) can be calculated. Quarterly groundwater elevation measurements are recommended over the first year of monitoring to determine how the flow direction and

gradient are affected by seasonal precipitation patterns. In coastal areas, daily tidal influences should be accounted for, and in areas close to agricultural lands, irrigation impacts on water level should be considered.

At monitoring locations where two or more wells are screened at different depths in the aquifer (well clusters), the vertical gradient can also be estimated. An understanding of vertical gradient is particularly important if the deeper portion of the surface aquifer is used for drinking water.

B.8 COLLECTING DATA ON POTENTIAL RECEPTORS

Identifying potential receptors that could be exposed to site contaminants is a critical component of developing the preliminary CSM and successfully implementing a risk-based approach to remediation. Appendix D.1.1 reviews types of potential receptors based on prevailing and/or expected site and surrounding land uses. The work plan should outline the steps that will be taken to identify or verify potential receptors and receptor exposure points at and downgradient from a site. Useful research and field methods for identifying human and ecological receptors are summarized in the following paragraphs.

B.8.1 Identifying Potential Human Receptors

Once contaminant sources, affected site media (e.g., soil, soil vapor, groundwater), and current and expected land uses have been identified in the preliminary CSM, receptor groups and exposure points must be determined. For Tier 1 screening-level assessments, generic receptor groups associated with general land uses are typically identified in the preliminary CSM. Most Air Force petroleum release sites are in industrial or commercial areas, and human receptors are initially categorized as onsite workers. If groundwater plumes extend downgradient from source areas into offsite and/or off-base areas, receptors associated with land uses in areas overlying the plume also must be considered. Common land uses and associated receptors include:

- Industrial/commercial - onsite workers;
- Recreational - recreators and maintenance workers; and
- Residential - residents and residential/utility construction workers.

Several resources are available to determine current and expected future land uses in areas potentially impacted by site contaminants, and to identify potential receptor exposure points. The base environmental staff should be familiar with current and planned future uses of sites on Air Force properties, and the type and source of the Base potable water supply. The status of the site (e.g., active, inactive, abandoned, scheduled for transfer to non-military owners) and its relative accessibility (e.g., in restricted area, fenced, along a public thoroughfare, or adjoining residential or recreational areas) are important considerations in identifying potential receptors. In addition to base and Air Force records, master plans, and land use planning documents for surrounding areas should be reviewed. In addition to identifying on-base water wells, consultation of state or county records to located potable-use water wells near the site (e.g., within a 1-mile radius) that may be screened in the affected aquifer is helpful

in identifying potential downgradient receptor exposure points. A well survey should be specified in the work plan for a risk-based remediation investigation.

Once Air Force and other local references and records have been reviewed and general receptor groups have been identified, types of potential exposures and exposure points can be refined during the field investigations. For instance, the types of site activities performed by workers can be better assessed (e.g., indoor exposure to vapors, intrusive activities, or outdoor nonintrusive activities), and features that might encourage unofficial activities that could result in receptor exposures (e.g., surface water drainages near unrestricted areas that might attract waders or fishermen) can be located. These site-specific exposures and locations of exposure points will be important in developing SSTLs if a Tier 2 evaluation is necessary.

In summary, Air Force, state, county, and municipal records can be good sources of land use and demographic information and data on the locations of groundwater wells that may serve as exposure points. Site visits can provide added detail on specific receptors and potential exposures that may occur onsite and in offsite areas affected by contaminants that have migrated from the source area. These details will form the basis for describing realistic exposure scenarios that can be used to develop SSTLs during Tier 2 risk-based analyses.

B.8.2 Identifying Ecological Receptors

As noted previously, in order to evaluate risks to the environment, it also is important to identify ecological receptors that could be exposed to unsafe levels of site contaminants. Many of the same references listed in Appendix B.8.1 to identify potential human receptors also can aid in identifying ecological receptors. For risk assessment purposes USEPA (1992a) suggests that only nondomesticated plant and animal species be considered, and the most emphasis is placed on determining potential risks to special-concern species and sensitive habitats. Special-concern species include those of legally protected status (e.g., threatened or endangered species, migratory birds) and those of social or economic importance (e.g., sport fisheries or game species). Sensitive habitats include critical habitat for special-concern species, and functionally valuable resources such as wetlands or reservoirs.

In heavily developed industrial, commercial, military, or residential areas, ecological receptors may not be at significant risk of exposure to site contaminants due to the lack of suitable habitat to sustain plant communities or wildlife populations. Land use plans, cultural and topographic maps, and aerial photographs can be used to identify areas that may provide suitable habitat for wildlife or aquatic organisms (e.g., undeveloped areas, fallow fields, parks, golf courses, ponds, streams, wetlands, etc.) and that fall within areas impacted by site contaminants. Exposure points can be identified as groundwater seeps or springs, gaining reaches of streams that intersect contaminant plumes, vegetated areas overlying shallow groundwater, and areas where soil contaminants are present at or near the surface. These potential exposure points can be verified during field investigations.

For the preliminary CSM, general ecological receptor groups such as terrestrial plants and wildlife, or aquatic organisms should be identified. To identify potential special-concern species that could be present in the immediate site vicinity, a variety of

references and resources should be reviewed. Good sources for information on vegetation types and associated animal populations at or near the site include:

- Base documents such as MAPs, environmental baseline surveys, environmental impact statements (EISs), redevelopment plans, and natural resource damage assessments;
- Base personnel who have knowledge of animals and fish species sighted on base in the vicinity of the site;
- Federal and state fish, wildlife, and land management agencies; and
- Local agencies, universities, and organizations involved in ecosystem management or study.

If special-concern species/habitats are not documented in the site vicinity, there usually is no need to provide an inventory of all species that may be present. Rather, examples of representative species that may be impacted by completed pathways are often sufficient. For example, if there is surface soil contamination at a heavily developed site, the only ecological receptors observed may be birds, such as pigeons. In the absence of suitable RBSLs for wildlife and plants, the need to identify individual species for risk analyses is usually unnecessary. If special-concern species are present and are likely to be exposed to site contaminants, the investigator should work closely with the appropriate resource management agency to determine risk-based cleanup goals that are adequately protective of such receptors. In most cases, however, it is acceptable to rely on the results of the Tier 1 human health RBSL evaluation to identify chemicals that could pose an unacceptable risk to terrestrial plants or animals, and to use federal or state surface water quality criteria for aquatic life RBSLs without considerations of individual species (see Appendix D.1.1.2 and D.2.1.2). This is reasonable because of the inherent conservatism of the generic human health RBSLs and the fact that federal and state water quality standards for surface water were developed to be protective of the most sensitive species.

In summary, classes of ecological receptors potentially exposed to site-contaminated media should be identified based on land use and habitat constraints as determined from base references, maps, and aerial photographs. The potential for special-concern species to be present in the impacted areas should be determined from base environmental documents and/or agency consultation. Potential exposure points should be identified first from maps and photographs, and then verified in the field. Site-specific conditions that affect the potential for exposure of ecological receptors (i.e., the likelihood of completed pathways) should be investigated during the site visits and through interviews with knowledgeable base personnel.

APPENDIX C

DOCUMENTING NATURAL ATTENUATION

For an exposure pathway to be complete, chemical contamination must be released from onsite sources into the environment, and then transported within and between different environmental media to potential receptor exposure-points (see Figure 2.1). If chemical contamination is not effectively released or transported, the exposure pathway may be incomplete, and no risk to the potential receptor will exist. Understanding how chemical contamination is released from sources and transported within the environment is critical to characterizing the potential risks that may have to be addressed by remediation. One of the key elements of the Air Force risk-based remediation strategy is an emphasis on documenting the impact of natural chemical attenuation processes on the release and transport of petroleum hydrocarbon contamination in the environment. At many petroleum release sites, natural chemical attenuation processes may be sufficient to interrupt or minimize the significance of potential exposure pathways because the contamination is attenuated at the source or within the environment. AFCEE has sponsored the development of several technical protocols that describe how to scientifically document the impact of these processes on chemical contamination (see Appendix G). This appendix highlights the major points of these technical protocols, especially as they relate to establishing risk-reduction requirements during risk-based evaluations.

C.1 ROLE OF NATURAL ATTENUATION IN THE REMEDIATION PROCESS

As noted in Section 2.1, the primary objective of the Air Force risk-based remediation strategy is to define and mitigate chemical contamination that may pose an unacceptable risk to potential receptors. The risk to any potential receptor group may be eliminated or at least minimized if hazardous concentrations of individual chemicals do not reach the point at which the receptor could come into contact with the chemical contamination (i.e., the receptor exposure-point). Natural chemical attenuation processes such as sorption, dilution (in air and water), volatilization, and biodegradation can minimize or even eliminate the potential for COPCs to reach potential receptor exposure-points at concentrations above appropriate risk-based cleanup levels. Consequently, determining whether chemical contamination could migrate to potential receptor exposure-points is one of the principal objectives of both streamlined and more comprehensive chemical fate assessments.

Considering the impact of natural chemical attenuation processes on petroleum hydrocarbon mass, persistence, mobility, and toxicity over time and distance at a site represents a departure from conventional risk assessment. In the past, current concentrations in the source area have been assumed to be representative of the

exposure-point concentration. This simplifying assumption has prompted the need to undertake remediation at sites where little if any risk is posed by site-related contamination. In many cases, particularly at petroleum-hydrocarbon-contaminated sites, natural chemical attenuation processes (supplemented with enforceable land and groundwater use restrictions) will be sufficient to prevent receptor exposure and eventually to attain risk-based cleanup goals in all impacted media. The natural chemical attenuation remedial option has been successfully implemented at numerous Air Force petroleum release sites (Wiedemeier *et al.*, 1995). Given these precedents, the AFCEE Remediation Matrix - Hierarchy of Preferred Alternatives identifies natural chemical attenuation (or intrinsic remediation) as the preferred remedial option for application at Air Force petroleum release sites.

C.2 FUNDAMENTALS OF PETROLEUM HYDROCARBON ATTENUATION

Natural chemical attenuation is defined as the positive effect of naturally occurring physical, chemical, and biological processes on reducing the mass of petroleum hydrocarbon contamination and/or minimizing the release of, or the extent of transport of, petroleum hydrocarbon compounds within environmental media (Hinchee *et al.*, 1992; Wiedemeier *et al.*, 1995). Nondestructive attenuation processes include volatilization, sorption, dilution, and dispersion. Biodegradation, which transforms contaminants into innocuous byproducts, is the primary destructive attenuation process. Contaminant destruction occurs through natural attenuation when native microorganisms biodegrade petroleum hydrocarbons without the engineered addition of oxygen or nutrients.

The Air Force has invested in developing methodologies to scientifically document natural attenuation processes for the following reasons:

- Contaminants are transformed to innocuous byproducts (e.g., carbon dioxide and water), not just transferred to another phase or location within the environment;
- The process is nonintrusive and allows continuing use of infrastructure during remediation;
- Current engineered remedial technologies such as groundwater pump and treat are only marginally effective and may pose a greater risk to potential receptors than natural attenuation (e.g., contaminants may be transferred into another medium during remediation activities);
- Sites can be prioritized, allowing those posing the greatest threat to potential receptors to be actively remediated, and identifying those that do not require active remediation; and
- Remediation by natural attenuation is far less costly than conventional, engineered remedial technologies (see Section 3).

The Air Force approach incorporates collection of site-specific data to document the operable natural attenuation mechanisms, as well as attenuation rates, rather than making generic assumptions regarding how chemicals should attenuate in similar environments. This site-specific approach provides a credible and sound basis for

estimating risk reduction over time and facilitates regulatory approval of risk-based remediation decisions. The *Technical Protocol for Implementing Intrinsic Remediation with Long-Term Monitoring for Natural Attenuation of Fuel Contamination Dissolved in Groundwater* describes three lines of evidence that can be used to support the viability of remediation by natural attenuation:

- Documented loss of contaminants at the field scale,
- Contaminant and geochemical analytical data, and
- Direct microbiological plate counts or “microcosm” studies.

The first line of evidence involves using historical trends in contaminant concentrations to show that a reduction in the total mass of contaminants is occurring at the site. The second line of evidence involves the use of geochemical data to show that decreases in contaminant and electron acceptor concentrations can be directly correlated to increases in metabolic byproduct concentrations. This evidence can be used to show that electron acceptor concentrations in groundwater are sufficient to support continued degradation of dissolved contaminants. This approach is described more fully in Appendix C.2.2. The third line of evidence can be used to show that indigenous biota are available and capable of degrading site contaminants. These “microcosm” studies are generally reserved for non-petroleum contaminants that may be difficult to degrade.

C.2.1 Nondestructive Attenuation Processes

Nondestructive attenuation processes can be described as those physical and chemical processes that may prohibit significant contaminant migration but may not result in a permanent reduction in contaminant mass. Examples of nondestructive attenuation processes include volatilization, sorption, dilution, and hydrodynamic dispersion. These processes should be evaluated at each site because they will influence the distribution and concentrations of chemical contamination and the potential risk to human or ecological receptors.

C.2.1.1 Sorption

All organic contaminants, including BTEX, are distributed between the soil and groundwater based on the nature and volume of the original release and on individual chemical sorptive properties and the sorptive properties of the soil. Sorption is the process whereby contaminants partition between the soil and groundwater and adhere to the soil particles comprising the aquifer matrix. The tendency for contaminants to sorb to source area soil particles in the unsaturated zone above the water table also influences the degree to which the contaminants will leach to groundwater when precipitation (or irrigation water) percolates through the soil column. Organic contaminants sorb to that portion of the soil matrix that is composed of organic carbon and fine clay particles. In most aquifers, the organic fraction tends to control the sorption of fuel hydrocarbons. Sorption of dissolved contamination onto the aquifer matrix results in slowing (retardation) of the contaminant relative to the average advective groundwater flow velocity, and can reduce COPC concentrations in groundwater. Benzene does not sorb readily to soil and is considered the most mobile

of the BTEX compounds (Abdul *et al.*, 1987). Conversely, contaminants such as polyaromatic hydrocarbons (PAHs) can be strongly sorbed to the aquifer matrix, and will be less mobile and less likely to be transported great distances from the source area.

C.2.1.2 Volatilization

Although not a destructive attenuation mechanism, volatilization does remove contaminant mass from the soil and groundwater. Partitioning of a contaminant between the liquid phase and the gaseous phase is governed by vapor pressure and Henry's Law. Thus, the Henry's Law constant of a chemical influences the tendency of a contaminant to volatilize into the soil gas or the atmosphere. Henry's Law constants for hydrocarbons range over three orders of magnitude, with the light aromatics (e.g., BTEX) having the highest volatility. The solubility and relative volatility of the BTEX compounds lead to a very strong enrichment of these compounds dissolved in groundwater relative to the other constituents of hydrocarbon fuels (Lyman *et al.*, 1992).

C.2.1.3 Hydrodynamic Dispersion and Dilution

Hydrodynamic dispersion, which includes mechanical dispersion and diffusion, is an important process causing dilution of contaminants dissolved in groundwater. Hydrodynamic dispersion is the process whereby a contaminant plume spreads out in directions that are longitudinal and transverse (parallel and perpendicular) to the primary direction of plume migration. The two components of hydrodynamic dispersion are mechanical dispersion and molecular diffusion. Hydrodynamic dispersion is the sum of mechanical dispersion and molecular diffusion. Mechanical dispersion is the dominant mechanism causing hydrodynamic dispersion at normal groundwater velocities. At extremely low groundwater velocities, molecular diffusion can become the dominant mechanism of hydrodynamic dispersion. In addition to dispersion-related dilution, dilution of contaminant concentrations in groundwater may also result from infiltration of fresh water into a water table aquifer as a result of precipitation (or irrigation) events.

C.2.2 Destructive Attenuation Processes

Destructive chemical attenuation processes result in the permanent removal of contaminant mass from the environment. Documenting and distinguishing the effects of destructive attenuation processes, such as biodegradation, from nondestructive attenuation processes is critical to evaluating the potential for natural attenuation to bring about a reduction in contaminant mass over time. The effectiveness of destructive attenuation processes at reducing contaminant mass at a site depends on how amenable the chemical is to biodegradation and whether the site is characterized by physical, chemical, and biological conditions favorable to such processes.

Over the past two decades, numerous laboratory and field studies have shown that microorganisms indigenous to the subsurface environment can degrade a variety of hydrocarbons (Wiedemeier *et al.*, 1995). In fact, almost all fuel-related hydrocarbons

are biodegradable. Microorganisms obtain energy to perform life functions (i.e., cell production and maintenance) by oxidizing organic matter, including organic contaminants. Microorganisms facilitate the degradation of organic compounds by transferring electrons from the electron donor (e.g., BTEX compounds) to available electron acceptors. Electron acceptors are elements or compounds that occur in relatively oxidized states and can participate in reduction/oxidation (redox) reactions involving these available electron donors. Electron acceptors commonly used in the biodegradation process include oxygen, nitrate, manganese, sulfate, ferric iron, and carbon dioxide.

Microorganisms facilitate fuel hydrocarbon biodegradation to produce energy for their use. The amount of energy that can be released when a redox reaction occurs or that is required to drive the reaction to completion is quantified by the Gibb's free energy (ΔG°) of the reaction (Stumm and Morgan, 1981; Bouwer, 1994; Chapelle, 1993; Godsey, 1994; Mueller *et al.*, 1994; Berg *et al.*, 1994). Microorganisms will facilitate only those redox reactions that will yield energy. By coupling the oxidation of fuel hydrocarbon compounds, which requires energy, to the reduction of electron acceptors (e.g., oxygen, nitrate, manganese, sulfate, ferric iron, and carbon dioxide), which yields energy, the overall reaction will yield energy.

Figure C.1 illustrates the natural order of microbially mediated redox processes based on the amount of free energy released for microbial use. In general, reactions yielding more energy take precedence over processes that yield less energy. As Figure C.1 shows, oxygen reduction would be expected to occur first in an aerobic aquifer because oxygen reduction yields significant energy. However, once the available oxygen is depleted and anaerobic conditions dominate the interior regions of the contaminant plume, anaerobic microorganisms can utilize other electron acceptors in the following order of preference: nitrate, manganese, ferric iron, sulfate, and carbon dioxide. Use of carbon dioxide as an electron acceptor results in the production of methane; therefore, this process is termed methanogenesis. As each electron acceptor that can be used to oxidize the contaminants is exhausted, the microorganisms begin to use other available electron acceptors. Each successive redox reaction provides less energy to the system, and each step down in redox energy yield would have to be paralleled by an ecological succession of microorganisms capable of facilitating the pertinent redox reactions.

As a result of the redox reactions described above, biodegradation causes measurable changes in groundwater geochemistry. For example, as a result of aerobic respiration, DO concentrations decrease. In anaerobic systems where sulfate is the primary electron acceptor, the sulfate is reduced to hydrogen sulfide, and sulfate concentrations decrease. As mentioned above, methane is produced as a result of the reduction of carbon dioxide. The relative contributions of different electron acceptors are site specific, and generally depend on their upgradient (background) concentrations. Figures C.2 and C.3 illustrate the patterns of electron acceptors and metabolic byproducts that were observed at one fuel-contaminated Air Force site. The measured distributions of electron acceptors and metabolic byproducts at this site provide evidence of natural biodegradation of dissolved contaminants. The figures indicate that areas containing elevated dissolved hydrocarbon concentrations are also characterized by depleted DO and sulfate concentrations (which are consumed during the biodegradation process) and

FIGURE C.1

EXPECTED SEQUENCE OF MICROBIALLY MEDIATED REDOX REACTIONS
AND GIBB'S FREE ENERGY OF REACTION

Process	ΔG_r°
Aerobic Respiration	-3202
↓	↓
Denitrification	-3245
↓	↓
Manganese Reduction	-3202
↓	↓
Iron (III) Reduction	-2343
↓	↓
Sulfate Reduction	-514
↓	↓
Methanogenesis	-136

Source: Wiedemeier et al. 1995. "Technical Protocol for Implementing Intrinsic Remediation With Long-Term Monitoring for Natural Attenuation of Fuel Contamination Dissolved in Groundwater." Prepared for AFCEE Technology Transfer Division.

elevated concentrations of reduced manganese and ferrous iron (which are produced during the biodegradation process).

Mass balance relationships can be used to determine how much contaminant mass can be degraded during each of these redox reactions. The stoichiometric relationship between the contaminant and the electron acceptor can be used to estimate the expressed assimilative capacity of the groundwater. Once the redox reactions operating at the site have been defined, it is possible to estimate how much contaminant mass can be assimilated or oxidized by available electron acceptors. This analysis, when coupled with biodegradation rate information (discussed in Appendix C.4.4), provides the basis for determining the potential for continued COPC mass reduction in saturated soils and groundwater.

Average background concentrations of all available electron acceptors at the example site are listed in Table C.1. These concentrations are used to calculate the expressed assimilative capacity of each electron acceptor (the mass of BTEX that can be biodegraded by each electron acceptor). For example, the chemical equations that describe the degradation of the BTEX compounds to carbon dioxide and water indicate that approximately 320 micrograms (μg) of BTEX is transformed for every 1,000 μg of

**TABLE C.1
ESTIMATE OF ASSIMILATIVE CAPACITY OF SATURATED SOIL AND
GROUNDWATER**

Electron Acceptor	Background Concentration ($\mu\text{g/L}$)	Initial BTEX Assimilative Capacity ^{a/} ($\mu\text{g/L}$)
Oxygen	5690	1820.0
Manganese ^{b/}	200	18.9
Ferric iron ^{b/}	10	0.5
Sulfate	9430	2045.6
	Total	3885.0

^{a/} Calculated based on the ratio of the total mass of electron acceptor required to oxidize a given mass of total BTEX.

^{b/} This represents the reduced form of the electron acceptor. Assimilative capacity is expressed only as an estimate. Does not represent actual total reservoir of electron acceptor to be exhausted.

DO consumed. With an average background DO concentration of 5,690 $\mu\text{g/L}$, the groundwater will have the capacity to assimilate 1,820 $\mu\text{g/L}$ of total BTEX (Table C.1). Table C.1 also presents the highest concentration of ferrous iron measured at the site. This concentration is used to "back-calculate" the expressed assimilative capacity that is attributable to ferric iron reduction. On the basis of these calculations, the saturated soils and groundwater at this site have the intrinsic capacity to eventually oxidize a total BTEX concentration of 3,900 $\mu\text{g/L}$.

The estimate identifies how much contaminant mass can be theoretically oxidized as one pore volume of clean groundwater travels through and is perfectly mixed with the plume. Because "perfectly mixed" conditions do not exist in any aquifer, the assimilative capacity estimate is a useful semi-quantitative measure of the aquifer's capacity to biodegrade dissolved hydrocarbons over time.

Electron acceptors can continually enter the system from upgradient flow. Furthermore, contaminant mass can be added to the system through dissolution or leaching from LNAPL or contaminated soils. This means that the assimilative capacity is not fixed as it would be in a closed system, and therefore should not be quantitatively compared to contaminant concentrations in the groundwater. The fate of COPCs in groundwater is dependent on the relationship between the kinetics of biodegradation and the solute transport velocities (Chapelle, 1994).

Following a hydrocarbon spill, soil microorganisms in the unsaturated zone also begin to use available soil gas oxygen to facilitate biodegradation. As the population of fuel-degrading microorganisms increases, the supply of soil gas oxygen is often depleted, creating anaerobic conditions in the vicinity of the spill. Carbon dioxide and methane are often produced as byproducts of the biodegradation of natural or refined hydrocarbons. Therefore, carbon dioxide and methane levels in soil gas are generally elevated in fuel-contaminated soils when compared to levels in clean background soils. Collection and analysis of soil gas samples for oxygen, carbon dioxide, and methane in addition to concentrations of volatile contaminants can determine both the location of contaminated soils and the degree to which biodegradation of unsaturated zone contaminants is occurring. Aerobic biodegradation of fuel hydrocarbons can be enhanced via *in situ* bioventing, which consists of the injection of air into oxygen-depleted soils. The use of soil gas surveys to determine bioventing feasibility and natural attenuation potential, and the performance of a field treatability test for bioventing are described more fully in Section 3 and in *Addendum One to the AFCEE Test Plan and Technical Protocol for a Field Treatability Test for Bioventing--Using Soil Gas Surveys to Determine Bioventing Feasibility and Natural Attenuation Potential* (See Appendix G).

C.3 STREAMLINED FATE AND TRANSPORT ESTIMATION METHODS

During the initial chemical fate assessment, potential exposure pathways are identified, and contaminant concentrations are compared to generic RBSLs to determine whether further action is necessary. Tier 1 RBSLs are based on conservative or maximum exposure assumptions (i.e., site chemical concentrations at or below the target levels are not expected to cause adverse health effects in human receptors), and can be obtained from "look-up" tables such as the example presented in the ASTM (1994) RBCA guidance. Chemicals exceeding RBSLs are retained as COPCs for further consideration, and those exposure pathways that pose the greatest risk to potential receptors are preliminary identified. In this way, further corrective action evaluations can be focused on those chemicals and environmental media that potentially pose a threat to human health or the environment.

As part of the streamlined assessment, it may be desirable to use simple analytical screening models to simulate the migration of contaminants in soil, surface water, groundwater, soil gas, and/or the atmosphere. Modeling objectives include assessing

whether significant contaminant concentrations can potentially reach potential receptors, and estimating the time to attain RBSLs without active remediation. Examples of Tier 1 migration models for a number of pathways relevant to petroleum releases are listed by ASTM (1995). The following paragraphs provide RPMs with an overview of these simple chemical fate estimation models.

C.3.1 Flux from Subsurface Sources

Two screening methods are recommended to determine if the air pathway is a potential concern at a site:

- Comparison of soil gas concentrations of COPCs to air quality RBSLs and Occupational Safety and Health Administration (OSHA) standards; and
- Comparison of soil gas TVH levels to lower explosive limits (LELs).

If ambient air quality data are not available, the maximum detected soil gas concentrations can be compared to air quality RBSLs to conservatively estimate ambient atmosphere COPCs. Soil gas data also may be compared to compound-specific, time-weighted-average (TWA) 8-hour permissible exposure limits (PELs) defined for air contaminants by OSHA. Total volatile hydrocarbon (TVH) concentrations derived from laboratory analyses of air samples or field measurements with hand-held instruments can be compared to the LEL for the fuel of concern to assess whether an explosive hazard exists. Comparison of compound-specific soil gas data to RBSLs and PELs will always be overly conservative because soil gas measurements do not reflect the exposure-point concentrations in aboveground (outdoor or indoor) ambient air. However, this approach provides an initial assessment of whether the air pathway is potentially significant.

C.3.2 Leaching from Contaminated Soils

Simple predictive leaching models can be used to assess the potential for soil COPCs to desorb from contaminated zones above or below the groundwater surface and dissolve into groundwater over time. Some soil leaching RBSLs are derived by multiplying the target groundwater quality concentration by an arbitrary factor (e.g., 20). These types of relationships are the simplest but least accurate ways to estimate whether soil contaminant concentrations may significantly affect groundwater quality. Tier 1 soil leaching RBSLs also can be back-estimated using a site-specific equilibrium partitioning calculation to establish residual soil concentrations that prevent leachate generation from exceeding target water quality concentrations in groundwater. The same relationship can be used to predict the groundwater concentration that would result from a given soil contaminant concentration. Pertinent equations are summarized in the ASTM (1994) RBCA guidance document.

The most commonly used method for expressing the distribution of an organic chemical between the aquifer matrix and the aqueous phase is the distribution coefficient, K_d , which is defined as the ratio of the sorbed contaminant concentration to the dissolved contaminant concentration:

$$K_d = \frac{C_a}{C_i} \quad \text{eq. C.1}$$

Where: K_d = distribution coefficient (L/kg)

C_a = sorbed concentration (mass contaminant/mass soil or $\mu\text{g}/\text{kg}$)

C_i = dissolved concentration (mass contaminant/volume solution or $\mu\text{g}/\text{L}$)

The higher the distribution coefficient, the greater the potential for sorption to the aquifer matrix. As equation C.1 indicates, once K_d is calculated, it can be used in conjunction with soil quality data (C_a) to estimate the concentration of contaminant that should be dissolved in the groundwater that is in contact with the contaminated soil (C_i).

Several researchers have found that if the distribution coefficient is normalized relative to the total organic carbon content of the soil, much of the variation in observed K_d values between different soils is eliminated (Dragun, 1988). Distribution coefficients normalized to total organic carbon content are expressed as K_{oc} . The following equation gives the expression relating K_d to K_{oc} :

$$K_{oc} = \frac{K_d}{f_{oc}} \quad \text{eq. C.2}$$

Where: K_{oc} = soil sorption coefficient normalized for total organic carbon content

K_d = distribution coefficient

f_{oc} = total organic carbon content (fraction) of the soil (mg organic carbon/mg soil)

K_{oc} values for many fuel compounds of interest can be obtained from the literature. Use of this relationship to estimate K_d is valid when organic carbon, and not clay minerals, provides the majority of sorption sites. In general, aquifers that have a high enough hydraulic conductivity to spread hydrocarbon contamination generally have low clay content. In these cases, the contribution of sorption to clay mineral surfaces is generally trivial. Table C.2 contains an example calculation of K_d for BTEX compounds using literature values of K_{oc} and measured, site-specific organic carbon concentrations. As shown in this table, retardation coefficients used to estimate the retarded contaminant migration velocity in the groundwater can be calculated using the K_d values. Use of the retardation coefficients is described in greater detail in Appendix C.3.3. In the absence of adequate site-specific data, a conservative K_d can be assumed based on experience or literature-based values; however, use of a value that is based on site-specific data is desirable so that the model will be more representative of actual conditions.

The K_d value is incorporated into a simple batch-flushing model presented by USEPA (1988) in which the total volume of contaminated soil is continuously or

TABLE C.2
CALCULATION OF DISTRIBUTION AND RETARDATION COEFFICIENTS

Compound	K _{oc} (L/kg ^{a/})	Average Fraction Organic Carbon ^{b/}	Average Distribution Coefficient ^{c/} K _d (L/kg)	Bulk Density (kg/L) ^{d/}	Effective Porosity ^{e/}	Average Coefficient of Retardation ^{f/}
Benzene	79	0.0028	0.221	1.70	0.25	2.50
Toluene	190	0.0028	0.532	1.70	0.25	4.62
Ethylbenzene	468	0.0028	1.310	1.70	0.25	9.91
m-xylene	405	0.0028	1.134	1.70	0.25	8.71
o-xylene	422	0.0028	1.182	1.70	0.25	9.03
p-xylene	357	0.0028	1.000	1.70	0.25	7.80

^{a/} From AFCEE natural attenuation technical protocol (Wiedemeier *et al.*, 1995)

^{b/} From laboratory analyses of site soil samples

^{c/} K_d = Average Fraction Organic Carbon x K_{oc}

^{d/} From laboratory analyses of moisture content, and assumed porosity and specific gravity.

^{e/} Literature value (Johnson, 1967).

^{f/} Coefficient of Retardation = 1 + [(bulk density x K_d)/effective porosity]

periodically flushed with groundwater. Contaminants sorbed to the soil matrix are predictively modeled to leach from the soil into the groundwater, and the resultant decrease in soil contaminant concentrations with time is simulated. In addition, the concurrent decrease in dissolved contaminant concentrations in groundwater also is simulated. An example batch-flushing model is shown in Table C.3. In the example case, the maximum soil concentration of xylenes measured at the site (39,600 µg/kg) was used as a starting point, and the calculated K_d value was used to derive the water concentration for day 0 (92,523 µg/L). As each new pore volume of groundwater comes in contact with the soil, a new equilibrium between the soil and groundwater is reached. In this way, both the soil and groundwater concentrations are reduced with each successive pore-volume "flush".

C.3.3 Estimating Plume Migration

Partial differential equations that describe groundwater flow and contaminant transport can be solved analytically or numerically. The type of model selected to simulate site conditions will depend on the results of data review and conceptual model development. A balance between simplifying assumptions and actual subsurface conditions must be reached to allow successful simulation of contaminant fate and transport. Screening-level analytical models are most appropriate for a streamlined analysis because they are simple and relatively easy to use, and they often can provide a good order-of-magnitude approximation of solute transport in relatively simple hydrogeologic settings. Analytical models can be used to:

- Estimate the migration distance of contaminants at a site over time;
- Predict exposure-point concentrations over time at varying distances from the source; and

TABLE C.3
SATURATED SOIL LEACHING CALCULATIONS USING A BATCH
FLUSHING MODEL

Days	Pore Volumes	Total Xylenes Soil Concentration (µg/kg)	Total Xylenes Water Concentration (µg/L)
0	0	39600.0	92523.4
195.1	1	19429.9	45397.0
390.2	2	9533.4	22274.2
585.3	3	4677.6	10928.9
780.4	4	2295.1	5362.3
975.5	5	1126.1	2631.0
1170.6	6	552.5	1290.9
1365.7	7	271.1	633.4
1560.8	8	133.0	310.8
1755.9	9	65.3	152.5
1951	10	32.0	74.8
2146.1	11	15.7	36.7
2341.2	12	7.7	18.0
2536.3	13	3.8	8.8
2731.4	14	1.9	4.3
2926.5	15	0.9	2.1

Shaded boxes show when predicted concentrations no longer exceed cleanup criteria.

- Assess whether natural attenuation may be a feasible remediation strategy at a given site.

Analytical models are best used for order-of-magnitude results because a number of potentially important processes can only be approximated. For example, terms describing a variety of chemical and hydrogeologic processes may be included in an analytical model, but the models usually are not capable of incorporating subsurface heterogeneity (spatial variation in chemical or hydrogeologic properties).

Examples of analytical models appropriate for an initial analysis are presented in the ASTM (1994) RBCA guidance document and Table C.4. BIOSCREEN is one example of a computerized analytical model that has been developed for the Air Force specifically for fuel spill applications (Newell *et al.*, 1996). BIOSCREEN is a screening tool for simulating the natural attenuation of dissolved hydrocarbons at petroleum fuel release sites. The model is based on the Domenico (1987) analytical solute transport model (Table C.4), which has the ability to simulate advection, dispersion, adsorption, and aerobic decay, as well as anaerobic reactions that have been shown to be the dominant biodegradation processes at many petroleum release sites. Conservative models can be constructed by assuming that only nondestructive chemical attenuation processes are operating (i.e., that the effects of biodegradation are insignificant). To improve model estimates, biodegradation rates can be added to the model using literature values or rates calculated from site-specific data.

**TABLE C.4
ANALYTICAL MODELS COMMONLY USED TO SIMULATE SOLUTE
TRANSPORT**

Processes Simulated	Description	References
One-Dimensional Models		
Advection, dispersion, linear sorption, and biodegradation - Constant Source Term	Solute transport in a semi-infinite system with a continuous source of contamination. Biodegradation is simulated using a first-order decay rate constant. Solute concentration is given as a function of time and distance.	Bear, 1972; van Gneuchten and Alves, 1982; and Wexler, 1992
Advection, dispersion, linear sorption, and biodegradation - Decaying Source Term	Solute transport in a semi-infinite system with a decaying source of contamination. Biodegradation is simulated using a first-order decay rate constant. Solute concentration is given as a function of time and distance.	van Gneuchten and Alves, 1982
Two-Dimensional Models		
Advection, dispersion, linear sorption, and biodegradation - Constant Source Term	Solute transport in a semi-infinite system with a continuous source of contamination. Biodegradation is simulated using a first-order decay rate constant. Solute concentration is given as a function of time and distance.	Wilson and Miller, 1978
Three-Dimensional Models		
Advection, dispersion, linear sorption, and biodegradation - Constant Source Term	Solute transport in a semi-infinite system with a continuous source of contamination. Biodegradation is simulated using a first-order decay rate constant. Solute concentration is given as a function of distance from the source and time.	Domenico, 1987 ^{a/}
Advection, dispersion, linear sorption, and biodegradation - Decaying Source Term	Solute transport in a semi-infinite system with a decaying source of contamination. Biodegradation is simulated using a first-order decay rate constant. Solute concentration is given as a function of distance from the source and time.	Domenico, 1987 modified for decaying source concentration

a/ Bioscreen® (Groundwater Services, Inc., 1996) is an expanded, computerized version of this model designed for use at petroleum fuel release sites.

C.4 ADVANCED FATE AND TRANSPORT ESTIMATION METHODS

In the event that site-specific target levels (SSTLs) are determined for the media of concern (e.g., soil, groundwater, surface water, and/or air), better estimates of exposure concentrations may be required. The calculation of SSTLs is described in Appendix D. SSTLs differ from Tier 1 RBSLs in the following ways:

- Site-specific data are used to calculate target cleanup levels;
- Human exposure to affected media is assumed to occur at an exposure point that is not necessarily at the source area; and
- The effects of natural attenuation of contaminant concentrations during transport from the source to the exposure point is documented in more detail in the SSTL calculation (Groundwater Services, Inc., 1995).

Understanding the effects of natural physical, chemical, and biological processes on COPCs is an important step in determining potential long-term risks associated with chemical migration in the environment. The behavior of COPCs under the influence of these processes must be quantified to:

- Predict the extent that soil COPCs could leach from mobile or residual LNAPL and dissolve into underlying groundwater;
- Assess the expected persistence, mass, concentration, and toxicity of dissolved COPCs over time at the site; and
- Estimate potential receptor exposure-point concentrations.

If destructive and nondestructive attenuation processes can minimize or eliminate the concentration of COPCs to which a receptor could be exposed, engineered remedial action may not be warranted because no reasonable completed exposure pathway exists, or completion of exposure pathways involving groundwater would not result in significant risks. Use of contaminant transport models (e.g., numerical groundwater flow and solute transport models) that are more sophisticated when compared to the screening models usually used during initial analysis may be appropriate to more accurately predict future contaminant migration and attenuation.

The following subsections describe more advanced methods to quantify how chemicals are released from sources and transported within and between environmental media. Documenting and presenting field-scale evidence of natural chemical attenuation processes is integral to a more advanced risk-based evaluation.

C.4.1 Attenuation in Soils

Soil contamination can sorb to soil particles, leach into groundwater, or volatilize into the soil gas or atmosphere. Therefore, to accurately assess the potential for soil COPCs to desorb and volatilize or dissolve into underlying groundwater over time, each of these processes must be accounted for. A number of predictive models are available to accomplish this objective. Information regarding vadose zone characteristics, such as permeability, porosity, moisture content, organic carbon content, and bulk density is generally required. These data can be collected during the site investigation (Appendix B), or reasonable site-specific assumptions can be developed. Recommended models are briefly described below in order of simple to more complex:

- The batch-flushing model described in Appendix C.3.2 can be used to simulate continual or seasonal flushing of contaminated soil with groundwater.
- The partitioning calculations used to derive soil RBSLs and referenced in Appendix C.3.2 can be used to predict the groundwater concentration that could result from a given vadose zone soil concentration.
- A more sophisticated soil leaching model used to derive soil SSTLs for cleanup of impacted soil can be used to estimate the groundwater concentration that would result from a given vadose zone soil concentration. One such model is described

in the RBCA guidance document issued by the South Carolina Department of Health and Environmental Control (1995). The referenced model uses a series of mathematical equations that quantify contaminant partitioning, transport, degradation, and dilution processes.

- Two commercially available, computer-based, one-dimensional analytical models can be used to simulate migration of contaminants in the vadose zone. VLEACH (CH2M Hill, 1990) simulates the leaching of a volatile, sorbed contaminant through the vadose zone. It models four main processes, including liquid-phase advection, solid-phase sorption, vapor-phase diffusion, and three-phase equilibrium. However, the current version of VLEACH is subject to a number of major assumptions, including homogeneous soil properties, steady-state unsaturated zone air flow, no free product, and no degradation. SESOIL (Bonazountas and Wagner, 1984) is designed to simultaneously model water transport, sediment transport, and pollutant fate. The model was designed to perform long-term simulations of chemical transport and transformations in the soil, and uses theoretically-derived equations to represent water transport, sediment transport on the land surface, pollutant transformation, and migration of the pollutant into the atmosphere and groundwater. Model output includes time-varying pollutant concentrations at various soil depths and pollutant loss from the unsaturated zone in terms of surface runoff, percolation of the groundwater, volatilization, and degradation. An expanded SESOIL user's guide has been developed by the Wisconsin Department of Natural Resources (Hetrick *et al.*, 1993).

Appendix B.5 and B.6 provide additional guidance on determining the role of biodegradation to naturally reduce the level of petroleum residuals in the soil. If site soil gas data indicate an abundance of oxygen (> 5 percent) and elevated carbon dioxide (> 3 percent) in contaminated soils, it can be assumed that atmospheric oxygen is available to the soil microorganisms that are employed in the task of biodegrading residual hydrocarbons. Typically, natural rates of biodegradation from 1 to 10 mg TPH/kg soil/day are common with 4 mg/kg/day as an average value (AFCEE, 1996). Natural soil aeration generally occurs in shallow, sandy soils where atmospheric oxygen can easily diffuse into the soil.

C.4.2 Weathering from Free Product

LNAPL can represent a long-term source of contamination because BTEX and other aromatic compounds will partition from the LNAPL into the groundwater. Maximum dissolved contaminant concentrations resulting from partitioning will occur when the groundwater and LNAPL reach equilibrium. Assuming that equilibrium is reached gives the most conservative modeling results.

The fuel-water partitioning coefficient, K_{fw} , is defined as the ratio of the concentration of a compound in the fuel to the compound's equilibrium concentration in water in contact with the fuel:

$$K_{fw} = \frac{C_f}{C_w} \quad \text{eq. C.3}$$

Where: K_{fw} = fuel-water partitioning coefficient [dimensionless]
 C_f = concentration of the compound in the fuel [M/L³]
 C_w = concentration of the compound dissolved in groundwater [M/L³]

Table C.5 lists values of K_{fw} for BTEX and trimethylbenzenes (TMBs) in jet fuel and gasoline.

Using the definition of K_{fw} presented above, the maximum (equilibrium) total dissolved COPC concentration resulting from the partitioning of the COPC from LNAPL into groundwater is given by:

$$C_w = \frac{C_f}{K_{fw}} \quad \text{eq. C.4}$$

This relationship predicts the concentration of dissolved COPC concentrations in the groundwater if the LNAPL is allowed to remain in contact with the groundwater long enough that equilibrium between the two phases is reached.

To complete partitioning calculations, samples of the mobile LNAPL must be collected from the site and analyzed to determine the type of fuel and its mass fraction of BTEX. From the mass-fraction BTEX data, the concentration of each BTEX compound in the fuel on a volumetric basis, C_f , can be calculated by using the relationship:

$$C_f = F_f \rho_f \quad \text{eq. C.5}$$

Where: ρ_f = Density of fuel
 F_f = Mass fraction of compound in the fuel

Using mass-fraction BTEX data from the LNAPL analyses, and the fuel-water partitioning coefficients presented in Table C.5 or elsewhere in the literature, the maximum dissolved COPC concentrations expected in groundwater caused by the partitioning of these compounds from the LNAPL can be calculated using equation C.4.

Example C-1: Equilibrium Partitioning Calculation

Mass fraction BTEX data from a sample of JP-4 LNAPL collected at a site with up to 3 feet of mobile LNAPL floating on the water table indicate that the mass fractions of benzene, toluene, ethylbenzene, and xylene are 0.000001, 0.00002, 0.0047, and 0.0009, respectively. Calculate the concentration of BTEX dissolved in groundwater in contact with the LNAPL that would be expected under equilibrium conditions.

Solution:

The first step is to determine the concentration of each compound in the LNAPL. The density of JP-4 jet fuel is 750,000 mg/L. The concentration of each compound is calculated using equation C.5. The results of this calculation are listed in Table C.6. The next step is to use the fuel/water partitioning coefficient (Table C.5) for each

TABLE C.5
FUEL-WATER PARTITIONING COEFFICIENTS (K_{fw}) FOR THOSE
COMPOUNDS MOST COMMONLY FOUND IN THE AQUEOUS PHASE IN
WATER IN CONTACT WITH JET FUEL OR GASOLINE

Compound	K_{fw} ^{a/} (JP-4 Jet Fuel)	K_{fw} ^{b/} (Gasoline)	K_{fw} ^{c/} (Gasoline)
Benzene	2,455	231	350
Toluene	2,754	895	1,250
Ethylbenzene	4,786	3,411	4,500
o-xylene	7,079	3,162	3,630
m-xylene	3,715	3,539	4,350
p-xylene	7,586	2,961	4,350
1,2,3-Trimethylbenzene	NA	NA	13,800
1,2,4-Trimethylbenzene	8,913	12,270	NA
1,3,5-Trimethylbenzene	NA	6,493	NA

a/ From experiments conducted by Smith *et al.*, 1981 (For JP-4)

b/ Model of Bruce *et al.*, 1991 (for gasoline)

c/ Model of Cline *et al.*, 1991 (for gasoline)

NA = not analyzed

compound and the concentration of each compound in the fuel to determine the equilibrium concentration in the groundwater using equation C.4. The results of this calculation are listed in Table C.6.

TABLE C.6
SOLUTION TO EXAMPLE C-1

Compound	Concentration in LNAPL (C_f , mg/L)	Fuel-Water Partitioning Coefficient (K_{fw}) ^{a/}	Concentration in Water ($\mu\text{g/L}$)
Benzene	0.75	2,455	0.31
Toluene	15	2,754	5.45
Ethylbenzene	3,525	4,786	736.5
Xylene	675	6,126 ^{b/}	110.2

a/ From Table C.5.

b/ Average of all isomers.

Alternate, less conservative models for nonequilibrium partitioning of fuel constituents from mobile LNAPL into groundwater are given by Hunt *et al.* (1988) and Johnson and Pankow (1992). These models are described in detail in Appendix C of the *Technical Protocol for Implementing Intrinsic Remediation with Long-Term Monitoring for Natural Attenuation of Fuel Contamination Dissolved in Groundwater* (See Appendix G).

Equilibrium partitioning of contaminants between LNAPL and groundwater can also be modeled using OILENS, which is one of the major modules of USEPA's Hydrocarbon Spill Screening Model (HSSM)(Charleneau and Weaver, 1993). The HSSM code was developed by USEPA's Robert S. Kerr Environmental Research Laboratory (now known as the National Risk Management and Research Laboratory) to aid in estimating the impacts of LNAPL releases on groundwater. OILENS can be used to estimate the equilibrium concentration of a chemical in contact with groundwater, and to calculate the mass-load leaching to groundwater from infiltrating precipitation.

C.4.3 Volatilization into Structures and Ambient Air

To assess whether subsurface sources (i.e., mobile LNAPL, contaminated soils, and/or dissolved contamination) can pose an unacceptable risk to potential onsite receptors via the inhalation exposure route, several different kinds of chemical flux and atmospheric transport equations can be coupled to simulate the concentrations of volatile COPCs present in outdoor ambient air under normal atmospheric conditions and the concentrations of volatile COPCs accumulating within onsite buildings. Most of the equations are based on the predictive contaminant migration equations presented by ASTM (1994). However, the equations for estimating flux into and resultant concentration within an enclosed space as presented in the ASTM (1994) guide appear to contain errors. Therefore, two simple models are recommended, the Farmer Model (USEPA, 1992) and the indoor air dispersion model (Michelson *et al.*, 1993).

Equilibrium partitioning equations can be used to estimate the mass of volatile COPCs that theoretically can partition from dissolved contamination, mobile LNAPL, and contaminated soil into the vapor phase. These equations assume linear partitioning and a constant, nondiminishing source (e.g., no reduction in the source term as a result of volatilization, biodegradation, or other attenuation mechanisms), and therefore are conservative. Alternately, measured soil gas concentrations can be used. Flux equations can then be used to estimate the mass of volatile COPCs that can migrate to the target mixing area (e.g., outdoor ambient atmosphere and/or indoor building space). Simple "box" mixing equations can be used to translate flux measurements into predicted exposure-point concentrations for air within the outdoor and indoor breathing zones. Equations, input parameters, and example calculations for a hypothetical site are shown in Table C.7. At this hypothetical site, available soil concentrations (C_{soil}) for each BTEX compound are used to estimate the outdoor and indoor ambient air concentrations of these COPCs. It should be emphasized that use of these equations requires that assumptions regarding site conditions be developed. Therefore, the final results may not be indicative of actual conditions. Whenever possible, site-specific flux monitoring and indoor air quality data should be collected so that overly conservative equations can be avoided.

C.4.4 Transport and Degradation in Groundwater

The use of groundwater models to simulate the fate and transport of dissolved BTEX is described extensively in the AFCEE Technical Protocol for Implementing Intrinsic Remediation with Long-Term Monitoring for Natural Attenuation of Fuel Contamination Dissolved in Groundwater. The discussion in the protocol document

Table C.7
Modeling Volatilization from Subsurface Media

Equations	Input Parameters		
Equilibrium Partitioning: Vapor Phase above Dissolved Contamination $C_{v,eq} = (H \cdot C_{w,eq})$	$C_{v,eq}$	Equilibrium vapor concentration (g/cm ³)	chemical-specific
	H	Henry's law constant (dimensionless)	chemical-specific
	$C_{w,eq}$	Equilibrium dissolved concentration (g/ml)	chemical-specific
Equilibrium Partitioning: Vapor Phase above LNAPL $C_{v,eq} = (x_i P_v M_w / RT)$	x_i	Mole fraction of contaminant i	chemical-specific
	P_v	Vapor pressure of contaminant i (atm)	chemical-specific
	M_w	Molecular weight (g/mol)	chemical-specific
	RT	Gas constant*temperature (cm ³ -atm/mol)	2.44E+04
Equilibrium Partitioning: Vapor Phase in Contaminated Soils $C_{v,eq} = (HC_{soil} p_s) / (\phi_w + k_s p_s + H \phi_a)$	C_{soil}	Concentration of contaminant in soil (g/g-soil)	chemical-specific
	p_s	Soil bulk density (g-soil/cm ³ -soil)	1.7
	ϕ_w	Volumetric content of pore water (dimensionless)	0.18
	k_s	Sorption coefficient (cm ³ -H ₂ O/g-soil)	chemical-specific
	ϕ_a	Volumetric content of pore vapor (dimensionless)	0.12
	ϕ_T	Total volumetric content in soil (dimensionless)	0.3
Measured Vapor Phase in Soils $C_{v,eq} =$ Maximum measured soil gas concentration	D_{air}	Diffusion coefficient in air (cm ² -day)	chemical-specific
	D_w	Diffusion coefficient in water (cm ² /day)	chemical-specific
Effective Vapor Diffusion Coefficient $D^{eff} = (\phi_a^{3.33} / \phi_T^{3.33}) * D_{air} + (1/H) * (\phi_w^{3.33} / \phi_T^{3.33}) * D_w$	R_v	Porous media retardation (dimensionless)	$k_s * p_s$
	$u_{v,max}$	Convective transport of vapors (cm/day)	100
Maximum Vapor Flux to Open Space $F_{max} = R_{v,lv,max} C_{v,eq} - (R_{v,lv,max} C_{v,eq}) / [1 - \exp(R_{v,lv,max} d / D^{eff})]$	d	Distance below ground to source (cm)	152.5
	L	Downwind length of source area (cm)	3658
Ambient Outdoor Concentration (g/cm³) $C_{outdoor} = F_{max} L / U_w \delta$	u_w	Wind speed (cm/day)	1.94E+07
	δ	Breathing height (cm)	1.89E+02
Maximum Vapor Flux to Enclosed Space $E_{max} = (D^{eff} C_{v,eq} \phi_a^{3.33}) / (\phi_T^2 d)$	A_{bldg}	Surface area of building (cm ²)	9.29E+06
	F_{crack}	Fraction of cracks in foundation (dimensionless)	0.01
	Air_{exch}	Air exchanges per day	13,140
Ambient Indoor Concentration (g/cm³) $C_{indoor} = (E_{max} A_{bldg} F_{crack}) / (Air_{exch} V_{bldg} MF)$	V_{bldg}	Volume of building (cm ³)	3.00E+09
	MF	Mixing factor (dimensionless)	0.5

Compound	H	x_i	P_v	M_w	C_{soil}	D_{air}	D_w	k_s	$C_{w,eq}$	Predicted $C_{v,eq}$	$C_{outdoor}$ (mg/m ³)	C_{indoor} (mg/m ³)	Measured $C_{v,eq}$	$C_{outdoor}$ (mg/m ³)	C_{indoor} (mg/m ³)
Benzene	0.232	0.030	0.125	95	3.40E-05	8.04E+03	0.95	0.190	6.9E-06	4.16E-05	1.34E+00	4.67E-06	2.10E-06	6.77E-02	2.36E-07
Toluene	0.265	0.285	0.037	92	3.20E-04	7.34E+03	0.81	0.674	1.0E-05	1.48E-04	1.70E+01	1.52E-05	3.00E-06	3.43E-01	3.08E-07
Ethylbenzene	0.265	0.133	0.009	116	1.50E-04	6.57E+03	0.73	0.477	2.4E-06	7.25E-05	5.87E+00	6.65E-06	1.20E-06	9.72E-02	1.10E-07
Xylenes	0.289	0.554	0.260	106	6.20E-04	6.22E+03	0.73	1.199	6.1E-06	7.62E-04	1.55E+02	6.62E-05	4.10E-06	8.34E-01	3.56E-07

also is applicable to the simulation of other COPCs in groundwater systems. Computer-based analytical models that incorporate the primary contaminant fate and transport processes, such as dispersion, sorption, and biodegradation [e.g., BIOSCREEN (Newell et al.), AT123D® (Yeh, 1993), or Solute® (Beljin, 1991)] can be used to simulate relatively simple, homogenous solute transport systems. As with analytical models, numerical models require the user to make some simplifying assumptions about the solute transport system. However, fewer simplifying assumptions must be made, so numerical models can simulate more complex systems. For this reason, numerical models can be used to more accurately simulate complex hydrogeologic systems or contaminant transport affected by complex sets of reactions. Heterogeneous and anisotropic hydrologic systems can be more accurately modeled using numerical models, as can transient systems (i.e., systems in which stresses, parameters, or boundary conditions change over time). Another advantage of numerical models is that most codes are capable of simulating contaminant sources that vary over time, allowing simulation of scenarios including source reduction through weathering or engineered remedial actions. For these reasons, numerical models are often appropriate for advanced assessments. Two numerical models that are recommended for use in advanced, BIOPLUME II and BIOPLUME III, are described in the following paragraphs.

The BIOPLUME II model incorporates advection, dispersion, sorption, and biodegradation to simulate contaminant plume migration and degradation. The model is based upon the US Geological Survey (USGS) Method of Characteristics (MOC) two-dimensional (2-D) solute transport model of Konikow and Bredehoeft (1978). The model was modified by researchers at Rice University to include a biodegradation component that is activated by a superimposed dissolved oxygen plume. Incorporating the work of Borden and Bedient (1986), the model assumes a reaction between dissolved oxygen and BTEX that is instantaneous relative to the advective groundwater velocity. BIOPLUME II solves the USGS 2-D solute transport equation twice, once for hydrocarbon concentrations in the aquifer and once for a dissolved oxygen plume. The two plumes are combined using superposition at every particle move to simulate the instantaneous, biologically-mediated, reaction between hydrocarbons and oxygen. Anaerobic decay can be simulated using a first-order rate constant, and sources of contaminants or oxygen can be simulated using injection wells or specified-concentration cells. Sorption is simulated using a retardation coefficient calculated as shown in Table C.2.

The BIOPLUME II model simulates anaerobic biodegradation by assuming that such degradation follows first-order kinetics. As with a large number of biological processes, anaerobic biodegradation can generally be described using a first-order rate constant and the equation:

$$\frac{C}{C_0} = e^{-kt} \quad \text{eq. C.6}$$

where:

C = Contaminant concentration at time t,

C₀ = Initial contaminant concentration,

k = biodegradation rate constant, and

t = Time (distance divided by groundwater velocity).

Two methods of calculating the biodegradation rate constant are currently available to quantify rates of biodegradation at the field scale and are applicable for use with available site data. Both methods are described in detail in the *Technical Protocol for Implementing Intrinsic Remediation with Long-Term Monitoring for Natural Attenuation of Fuel Contamination Dissolved in Groundwater*. The first method involves the use of biologically recalcitrant compounds found in the dissolved BTEX plume (e.g., TMBs) that can be used as conservative tracers. However, the degree to (and conditions under) which the tracer compounds are resistant to biodegradation is sometimes questionable. Therefore, the second method, proposed by Buscheck and Alcantar (1995), is recommended for use in most situations. This method involves interpretation of a steady-state contaminant plume configuration and is based on the one-dimensional, steady-state analytical solution to the advection/dispersion equation presented by Bear (1979). Decay rates derived from this method include biodegradation resulting from both anaerobic and aerobic processes operating along a given path; however, in the absence of DO, the calculated rate is equivalent to the anaerobic decay rate.

BIOPLUME III is the updated version of BIOPLUME II and has been modified to allow simulation of biodegradation dependent on multiple electron acceptors. The resulting code will allow simulation of first-order biodegradation, instantaneous reactions between electron acceptors [DO, nitrate, iron (III), sulfate, and carbon dioxide] and the dissolved contaminant plume, and Monod kinetics. This model also incorporates graphical pre- and post-processors. BIOPLUME III is currently available through the EPA at internet address: <http://www.epa.gov/ada/models.html>.

The migration and attenuation of a group of compounds having similar properties (e.g., the BTEX compounds) can be simulated by using model input values that are representative of the average properties of the group. The subsurface behavior of individual indicator compounds also can be simulated by using input values that are representative of that compound. Benzene often is used as an indicator compound at fuel spill sites because it is relatively toxic (with low target cleanup levels), mobile, and amenable to biodegradation. Concurrent simulation of a less mobile compound (e.g., naphthalene) can be used to span the range of potential migration behaviors.

APPENDIX D

DEVELOPING RISK-BASED CLEANUP GOALS

The risk-based corrective action process involves a tiered approach in which assessment and resultant remediation activities are tailored to site-specific conditions and risks (ASTM, 1994). Increasingly complex levels of data collection and risk evaluation may be performed to establish the type and magnitude of remediation required to reduce or eliminate unacceptable risks at a particular site. The tiered approach provides the flexibility to replace potentially overly conservative, nonsite-specific exposure assumptions with site-specific information, while still providing the same level of human health and environmental resource protection. This is accomplished primarily by replacing nonsite-specific (i.e., default) assumptions about how chemicals behave in the environment and how receptors may be exposed with site-specific data and assumptions that are more representative of actual site conditions and realistic exposure pathways for human and ecological receptors.

As mentioned in Section 2.3.1, three basic tiers of site evaluation (e.g., data analysis) have been established in the RBCA process:

- Tier 1 or screening-level evaluations;
- Tier 2 or site-specific evaluations; and
- Tier 3 or advanced site-specific evaluations.

This section summarizes the primary elements of each tier, with emphasis placed on how remediation target levels are established.

D.1 CONDUCTING A SCREENING LEVEL (TIER 1) EVALUATION

A Tier 1 or screening level evaluation provides an Air Force RPM with the means to quickly identify whether a particular petroleum release site warrants additional investigation and evaluation. Thus, the Tier 1 evaluation is the starting point for the Air Force risk-based remediation approach, and can be used to prioritize funding requests and response actions.

The basic "tool" of a Tier 1 evaluation is the set of criteria defined as Tier 1 risk-based screening levels (RBSLs). RBSLs are conservative (health protective), generic screening criteria that define the residual amount of a contaminant that can remain in onsite environmental media and not present an unacceptable risk to potential receptors. This handbook recommends the use of land-use-based RBSLs derived using reasonable maximum exposure (RME) assumptions, as defined by the USEPA, and defensible toxicity values. These types of RBSLs can:

- Be defined as "evergreen," because they represent the concentration at which there should be no unacceptable threat to potential receptors;
- Assist in determining whether additional site characterization data are required to make a credible RBCA decision. (For example, if the reporting limits for existing site analytical data are above the applicable Tier 1 RBSL, additional data would be required to complete a defensible Tier 1 evaluation.);
- Provide a defensible "benchmark" for initially evaluating whether a site warrants additional investigation and/or evaluation (i.e., provide the basis for advancing to a Tier 2 evaluation), and to aid in identifying data gaps;
- Assist in determining whether interim remedial action is required; and
- Be used to support or justify a no further response action planned (NFRAP) decision for a site.

Appendix A presents the case study for Site OT-45 at Wurtsmith AFB, where a Tier 1 evaluation was used to support a NFRAP decision. Appendix A also presents the case study for Site ST-27 at Charleston AFB, where a Tier 1 evaluation was used to identify the need to implement an interim action to mitigate potential immediate hazards. The case studies in Appendix A illustrate how a Tier 1 evaluation can be used to prompt implementation of a risk-based corrective action and/or a Tier 2 evaluation.

D.1.1 Identifying Applicable Risk-Based Screening Levels (RBSLs)

RBSLs are based on RME assumptions for various land use scenarios (e.g., industrial, commercial, residential). RBSLs for human receptors can be either health protective or designed to mitigate nuisances associated with chemical contamination (e.g., taste and odor). The latter type of RBSLs are called aesthetic criteria, and should be carefully evaluated to determine if they apply to a site before being used in any Tier 1 evaluation.

In order to select (or develop) appropriate RBSLs and perform a credible Tier 1 evaluation for a site, basic information about the current and potential future land and groundwater uses at or downgradient from the site must be known. Typically, RBSLs for the residential land use scenario are more conservative/stringent than those for industrial or commercial scenarios because unrestricted and prolonged (i.e., 30-year) exposure to site media is assumed. Therefore, carefully evaluate the types of activities that exist, or could potentially exist, at a site before selecting RBSLs for a particular land and groundwater use scenario. Most published RBSLs assume ingestion of onsite groundwater by a specific receptor group (e.g., residents or industrial onsite workers). While this is seldom the case on Air Force installations, these conservative RBSLs (i.e., unrestricted or residential) may need to be established for onsite media if the potential for off-site migration exists and will not be evaluated as part of the Tier 1 evaluation. In general, an industrial land use RBSLs is appropriate for an Air Force site if:

- Residential land use currently does not occur at or near the site;

- A future residential land use scenario is unrealistic (based on the Base land use master plan, local zoning requirements, access control, proposed property transfer plans, etc.); and
- It can be reasonably anticipated that the future use of the site will be restricted to industrial activities.

In most instances, petroleum and other contaminant release sites on Air Force bases meet this basic definition of an industrial site. Recently published USEPA (1995) guidance on establishing land use for CERCLA remedial evaluations provides useful information on how best to define and defend land use assumptions. However, it may be prudent to consult with a professional risk assessor if uncertain about how best to select appropriate RBSLs for a particular site. It is important to emphasize that any assumptions regarding land use should be included and explained in the preliminary CSM (Section 2.1.3).

Once the appropriate land use category has been defined, the types of exposure pathways to be considered in the Tier 1 evaluation must be defined. This means that the preliminary CSM needs to be reviewed to determine which pathway-specific RBSL should be used to drive Tier 1 conclusions. In all cases, the most stringent RBSL for a given exposure pathway that is, or could be, completed at the site should be used. For example, site data may indicate that soils may be a secondary contaminant source to groundwater (via leaching), and that onsite workers could also dermally contact soils. Two types of RBSLs would be applicable: a soil RBSL that is protective of underlying groundwater quality (commonly called soil leaching RBSL) and a direct-contact (health-protective) soil RBSL. The soil leaching RBSL typically is more stringent than health-protective RBSLs for industrial sites. Because a Tier 1 evaluation for soils is usually driven by the need to protect underlying groundwater, this handbook describes several simple estimation methods to quickly test the "reasonableness" of the soil leaching RBSL (Appendix C).

The last step in identifying applicable RBSLs is defining the target risk range for the Tier 1 evaluation. In order to adequately explain, justify, and/or defend the selection of any set of Tier 1 RBSLs, it is important that the Air Force RPM possess a basic understanding of the risk target levels used to develop the criteria. Generally speaking, acceptable target risk ranges for carcinogens (e.g., benzene) fall between 10^{-5} to 10^{-4} (USEPA, 1991b). These risk ranges correspond to an added lifetime cancer risk of 1 in 1,000,000 to 1 in 10,000 for people exposed to site contamination. Because the Tier 1 criteria are used primarily to screen out detected analytes from further evaluation, the RBSLs for carcinogens typically are based on an extremely protective 10^{-6} target risk level (commonly referred to as a *de minimis* risk level, meaning that a 1 in 1,000,000 risk level is so small as to be of negligible concern [ASTM, 1995]). Thus RBSLs can be construed as very health protective, given that the "normal background level" of cancer in the general population is about one in three persons (30 to 35 percent) (USEPA Region 8, 1994). For carcinogens, USEPA (1996) believes that setting a 10^{-6} target risk level for individual chemicals and pathways generally will lead to cumulative risks within the 10^{-4} to 10^{-6} risk range for the combinations of chemicals typically found at contaminated sites.

Just as important as the carcinogenic target risk levels discussed above are the noncarcinogenic hazard quotients (relevant to analytes that cause non-tumor-related illnesses). The acceptable target hazard quotient for noncarcinogens (e.g., toluene) is set by USEPA (1989) at less than or equal to 1. This target hazard quotient is used to calculate a soil concentration below which it is unlikely that even sensitive populations would experience adverse health effects.

D.1.1.1 RBSLs for Human Receptors

Several federal and state regulatory agencies have already established or adopted Tier 1 RBSLs for human receptors to be used to perform Tier 1 evaluations (AAR, 1996). Use of available and applicable RBSLs for human receptors is preferable to development of RBSLs. This will streamline the process by:

- Promoting consistency among screening-level evaluations;
- Encouraging regulatory approval of remedial decisions based on Tier 1 evaluations (familiarity with published values increases the comfort level with resulting decisions); and
- Preventing "reinvention of the wheel" for every Tier 1 evaluation.

Sources of published RBSLs for human receptors include:

- USEPA (1996) Soil Screening Guidance (EPA/540/R-96/101);
- Regional USEPA RBSLs [some of the 10 USEPA Regions (e.g., USEPA Region 3) have adopted some type of screening-level criteria];
- State UST or non-UST petroleum remediation program guidance (AAR, 1996) and ASTM (1995) example RBSLs.

Although the USEPA (1996) has developed soil screening levels (SSLs) for most of the major petroleum hydrocarbon compounds commonly found in Air Force petroleum sources (e.g., BTEX, naphthalene), a more comprehensive list of soil RBSLs has been developed by USEPA Region 3 (1996). The Region 3 soil RBSLs may prove to be more acceptable to state regulators in the absence of specific program guidance because the values have been extensively peer reviewed and address industrial as well as residential land use scenarios. To include industrial-based RBSLs for groundwater use, the ASTM (1995) values are included, as USEPA does not currently provide these in a look-up format. Table D.1 presents a combination example look-up table adapted from USEPA Region 3 and ASTM guidance for common analytes encountered at petroleum releases sites.

In those rare cases where RBSLs for human receptors need to be developed as part of a specific Tier 1 evaluation, available USEPA and ASTM references on developing risk-based target concentrations should be reviewed. Because RBSLs are generic screening criteria, it is not appropriate at this stage to incorporate site-specific data and assumptions about chemical fate and potential exposure pathways. Rather, RBSLs should be based on standardized exposure assumptions that conservatively represent

**TABLE D.1
RECOMMENDED TIER 1 RBSLS FOR FREQUENTLY ENCOUNTERED
ANALYTES**

Basis : C=carcinogenic effects (values based on 10 ⁻⁶ target risk level) E=EPA draft Soil Screening Level N=noncarcinogenic effects (values based on an HQ of 1) S=soil saturation concentration															
Contaminant	V O C	Risk-Based Concentrations For:										Soil Screening Levels-Transfer from Soil to Groundwater ^{c/}			
		Groundwater (Ingestion) Residential ^{b/}	Groundwater (Ingestion) Industrial ^{b/}	Ambient Air ^{c/}	Fish	Soil (Ingestion)		mg/kg	mg/kg						
		µg/L	µg/L	µg/m ³	mg/kg	Residential ^{c/}	Industrial ^{c/}								
Benzene	x	2.94	C	9.87	C	0.22	C	0.11	C	22	C	200	C	0.02	E
Ethylbenzene	x	3,650	N	10,200	N	1,000	N	140	N	7,800	N	200,000	N	5	E
Benzo[a]pyrene		0.0117	C	0.0392	C	0.001	C	0.0004	C	0.088	C	0.78	C	4	E
Naphthalene		146	N	409	N	150	N	54	N	3,100	N	82,000	N	30	E
Toluene	x	7,300	N	20,400	N	420	N	270	N	16,000	N	410,000	N	5	E
Xylene (mixed)	x	73,000	N	> S	N	7,300	N	2700	N	160,000	N	1,000,000	N	74	E

Adapted from USEPA Region 3 (1996) Risk-Based Concentration (RBC) Table and ASTM (1995) RBCA Guidance.

^{a/} Compounds with a Henry's Law constant greater than 10⁻⁵ were considered volatile.

^{b/} Values from ASTM (1995) Risk-Based Screening Level (RBSL) Look-up Table.

^{c/} Values from USEPA Region 3 (1996) Risk-Based Concentration Table.

potential land use scenarios for a particular site. Appendix G presents a list of references that should be consulted if RBSLs are to be developed.

D.1.1.2 RBSLs for Ecological Receptors

In addition to potential human receptors, a Tier 1 evaluation must consider potential nonhuman (i.e., ecological) receptors and other environmental resources that could be impacted by site contaminants. The preliminary CSM developed for a site should address the potential for ecological receptors to be involved in completed exposure pathways. Most Air Force petroleum release sites are in developed, industrial areas that lack suitable habitat to support resident ecological receptors. Therefore, the potential for ecological receptors to be exposed to site contaminants typically is low at Air Force petroleum release sites. In fact, the ASTM (1994) *Emergency Standard Guide for Risk-Based Corrective Action Applied at Petroleum Release Sites* and related resources references (Newell *et al.*, 1996) do not address the need to complete Tier 1 evaluations for potential ecological receptors. However, remedial decisions for a petroleum release site could conceivably be driven by the need to prevent adverse impacts on ecological receptors or sensitive habitats such as wetlands.

Potentially completed exposure pathways involving ecological receptors, which may include nondomesticated terrestrial plants, terrestrial wildlife, and/or aquatic life, should be defined during development of the preliminary CSM. In addition to information on land use, information about the general characteristics of the impacted area in terms of types, availability, and quality of habitat for various species need to be

collected. For example, if the site is in a heavily developed, high-traffic industrial area, or if contaminated media occur only at depth (e.g., > 10 feet), ecological receptors may not be present or pathways from contaminated media may be incomplete. However, if, for instance, a perennial surface water body is present at or near the site and contamination could conceivably adversely impact surface water quality, Tier 1 RBSLs for aquatic life may be applicable. Guidance on identifying ecological receptors that may be involved in completed contaminant exposure pathways at a given site is provided in Appendix B (B.8.2) of this handbook.

RBSLs for ecological receptors are less readily available and less universally accepted than those for human receptors. Generally, only aquatic life RBSLs for screening of contaminants in surface water are widely accepted. Possible sources of published RBSLs for ecological receptors include:

- Federal water quality criteria (USEPA, 1986) and state surface water quality standards developed to be protective of the most sensitive aquatic species. Often there are criteria established for both chronic (long-term) and acute (short-term) exposures. Where available, the chronic values should be used as RBSLs. Be sure to select the appropriate standards for either marine or freshwater, depending on the type of water body affected. Because the federal criteria are not promulgated, state standards should be used as RBSLs for protection of aquatic life whenever they are available.
- Toxicological benchmarks developed in the technical literature for ecological receptors exposed to contaminated media through ingestion or uptake (e.g., no-observed-effect levels, or NOELs, for terrestrial wildlife, and agricultural phytotoxicity guidelines for terrestrial plants).
- Sediment quality criteria developed to be protective of benthic aquatic organisms (e.g., National Oceanic and Atmospheric Administration, 1990; Long and Morgan, 1991; USEPA, 1993a).

In the absence of widely accepted RBSLs for terrestrial plants and wildlife, it is often acceptable to regulators to assume that matrix-specific RBSLs applied during a Tier 1 analysis for human receptors will identify COPCs for ecological receptors exposed to the affected medium. This assumption, which should be clearly stated in the Tier 1 analysis, eliminates the need to conduct a separate Tier 1 screening analysis for terrestrial ecological receptors at most sites. At sites where aquatic receptors may be exposed to site contaminants in surface water, state or federal water quality criteria should be adopted as the RBSLs for this medium. Basic procedures involved in ecological risk assessments may be helpful in making decisions regarding the need to conduct a Tier 1 analysis for ecological receptors at a given site. Overviews of these procedures are presented in the USEPA (1992a) *Framework for Ecological Risk Assessment* and the *Tri-Service Procedural Guidelines for Ecological Risk Assessments* (Wentzel *et al.*, 1996). However, because of the industrial nature of most Air Force petroleum release sites and the typically subsurface nature of the contamination (i.e., the lack of completed exposure pathways to ecological receptors), completing Tier 1 evaluations that use ecological RBSLs will be the exception rather than the rule, and rarely will RBSLs for ecological receptors drive the conclusions of a Tier 1 evaluation.

D.1.2 Comparing Site Contaminant Levels to RBSLs

Once applicable RBSLs for each detected chemical are identified, the Tier 1 evaluation process is very straightforward. The Tier 1 evaluation consists of comparing representative exposure-point concentrations from recent site sampling events to applicable RBSLs. It is important to use the most recent data (the Air Force generally recommends evaluating the two most recent sampling events) to compare with RBSLs to provide the best "snap-shot" of potential risk to human health and the environment. Although common statistical methods can be used to determine analyte exposure-point concentrations, currently defined by USEPA (1992b) as the 95-percent upper confidence limit (UCL) of the arithmetic mean for Superfund risk assessments, often insufficient data are initially collected at petroleum release sites to support statistical calculations. Therefore, rather than complicate the Tier 1 process with requirements for estimating exposure-point concentrations from analytical data, the Air Force generally recommends that the Tier 1 evaluation simply consist of a comparison of maximum detected site concentrations to applicable RBSLs. Table D.2 presents an example Tier 1 RBSL comparison table format that can be used to quickly summarize the major elements and conclusions of a Tier 1 evaluation.

Analytical data for soil and groundwater are usually available for most sites. However, one of the most common RBSLs for the volatile petroleum hydrocarbon compounds is based on protection of indoor and outdoor ambient air quality. If no ambient and/or indoor air samples were collected during site characterization efforts (which is typical), it is possible to estimate the concentration in air due to volatilization from subsurface sources such as contaminated soils and groundwater, or simply use soil

**TABLE D.2
EXAMPLE TIER 1 SCREENING TABLE**

Detected Analyte	Units	Maximum 1995 Concentration	Maximum 1996 Concentration	Risk-Based Screening Levels		
				Nonintrusive Worker Health Based (Inhalation)	Intrusive Worker Health- Based (Ingestion or Dermal)	Protective of Underlying Groundwater
Benzene	mg/kg	5.4	4.8	0.5	99	0.02
Toluene	mg/kg	16.3	14.7	520	200,000	5
Ethylbenzene	mg/kg	9.4	8.2	260	100,000	5
Xylenes	mg/kg	32.6	31.9	320	10 ⁶ (1,000,000)	74
Chlorobenzene	mg/kg	4.6	3.8	94	41,000	0.6
Naphthalene	mg/kg	40.1	38.7	180	41,000	30
1,2,4- Trimethylbenzene	mg/kg	5.3	4.4	98	100,000	--
1,3,5- Trimethylbenzene	mg/kg	8.7	9.3	98	100,000	0.26

Conclusion: Tier 1 soil COPCs are benzene, toluene, ethylbenzene, chlorobenzene, naphthalene, and 1,3,5-trimethylbenzene. All soil COPCs, except benzene, identified due to exceedance of Tier 1 soil leaching RBSL (i.e., could leach from soils and adversely impact groundwater quality).

gas (or better still, soil flux) measurements as surrogate comparison levels to inhalation-based RBSLs (this is a conservative approach because soil gas concentrations are likely to be significantly higher, perhaps orders of magnitude so, than actual indoor and outdoor air concentrations). Appendix C (C.4.2) summarizes several simple estimation methods that can be used to quickly estimate exposure-point concentrations in air based on site analytical data for other media.

Tier 1 Action Decision

Figure 2.3 outlines the major decision points in the Air Force risk-based remediation strategy. Generally, the comparison of RBSLs to site contaminant levels will result in one of the following outcomes:

1. Maximum Detected Site Concentrations \leq Applicable RBSLs

To assess whether an immediate site closure (or NFRAP) decision document can be prepared, measured site concentrations must be equal to or below applicable RBSLs considering on- and offsite receptors under current and future conditions. In other words, the RBSLs selected for comparison to site concentrations must be conservative enough (i.e., based on RME scenarios) to protect the potentially most exposed human receptor, under any realistic current or future land use scenario. Therefore, additional chemical fate assessment may be required as part of the Tier 1 evaluation in order to gain regulatory and public support for an NFRAP decision (this issue is discussed further below). Remember that the burden of proof is on the Air Force to adequately demonstrate that risks to current and especially future potential receptors are acceptable. Once this is accomplished, the RPM can then secure regulatory approval for an NFRAP decision. As discussed below, this may result in an agreement to monitor for some period of time to ensure future site conditions support this finding.

2. Maximum Detected Concentrations $>$ Applicable RBSLs

The principal requirement at this point is to determine which of the following options is necessary or desirable, to protect human health and the environment:

- Option 1--Take immediate (interim) action to prevent unacceptable hazards;
- Option 2--Implement a long-term correction/remedial action plan to achieve RBSLs using low-cost source reduction technologies; or
- Option 3--Conduct a site-specific (Tier 2) evaluation to more accurately (and realistically) estimate potential risk to human health and the environment and, if necessary, to define risk reduction requirements.

Option 1--It is important to emphasize that a Tier 1 evaluation can aid in identifying immediate hazards (external, such as explosive, or internal, such as a chronic illness) at a particular site. If the Tier 1 evaluation suggests that current or potential future receptors could be exposed to site-related contamination at concentrations significantly above the RBSLs or that such exposure could occur within the next 2 years, some type

of immediate response action may be necessary. Such sites would be classified as having a high relative risk (DoD, 1994). Appendix A presents the case study for Site ST-27 at Charleston AFB, where the Tier 1 evaluation demonstrated the need to implement immediate action to mitigate the potential for explosive and inhalation hazards from subsurface VOC vapor concentrations.

Option 2--Implementation of low-cost source reduction technologies as part of a long-term corrective action plan (CAP) may be more cost-effective than conducting a Tier 2 evaluation. If the action decision is to implement a low-cost, long-term source reduction CAP, then Tier 1 evaluation should provide sufficient information/evidence to show whether low-cost source reduction technologies could be used to achieve RBSLs. The application of low-cost source reduction technologies at this point could result in significant time and cost savings, because a Tier 2 evaluation need not be completed, reviewed, and approved.

On the other hand, in the absence of a more site-specific evaluation, the Tier 1 RBSLs would be identified as the target remedial objectives for the petroleum release site. Although suitable for screening analysis, published RBSL values are rarely representative of actual site conditions; the values are conservative, and usually overestimate risk. By deciding to remediate without additional evaluation, you may have to meet more stringent cleanup goals than are necessary to provide the desired level of health protection.

Option 3--Completing a more site-specific (Tier 2) evaluation rather than implementing a RBCA will ensure that the final remedial action planned for a particular site is tailored to specific site conditions and risks. Depending on the complexity of the site, a Tier 2 evaluation may represent a relatively small incremental effort, or it may represent a significant investment in comparison to a Tier 1 evaluation. The tradeoff is that long-term compliance costs will be minimized by establishing less stringent, yet health-protective cleanup goals. Section 3.2 summarizes the major elements of establishing SSTLs as part of a Tier 2 evaluation.

It is worth noting that the Air Force risk-based remediation process differs slightly from the ASTM RBCA process at some key points. For example, under the Tier 1 analysis, completion of a streamlined (Tier 1-associated) chemical fate assessment is not strictly provided for in the ASTM RBCA framework. ASTM (1995) guidance states the following:

If the concentrations of chemicals of concern at the point of compliance are less than the target levels (i.e., RBSLs), but the user (i.e., *the Air Force RPM*) is not confident that data supports the conclusion that concentrations will not exceed target levels in the future, then the user institutes a monitoring plan to collect data sufficient to confidently conclude that concentrations will not exceed target levels in the future. When this data is collected (or if the user is initially confident that concentrations will not exceed target levels in the future), then no additional corrective action activities are necessary, and the user has completed the RBCA process. In practice, this is often accompanied by the issuing of a no-further-action letter by the oversight regulatory agency.

In practice, regardless of the Air Force RPM's confidence in the data, the Air Force has found that in order to gain regulatory support for an NFRAP decision, two action items are often necessary:

1. Presentation of a predictive analysis of chemical fate to evaluate nonhealth-related impacts to natural resources and/or health-related impacts to receptors, as requested by state agencies that may want additional comparisons. For example, even though the RPM selected receptors based on likely exposure scenarios, some state agencies will request a "worst-case" evaluation before allowing closure of the site. Furthermore, there may be instances where maximum site concentrations exceed the appropriate RBSLs, but it can be clearly demonstrated that current risk is acceptable and that (through use of a predictive analysis) the RBSLs can be achieved within a few months to two years, thereby eliminating future risk concerns.
2. Monitoring of site conditions (e.g., groundwater) for some period of time. To address the first issue, the use of simple to sophisticated models (the same range of models typically recommended for use in Tier 2 and Tier 3 evaluations) to predict chemical fate to support the NFRAP recommendation is sometimes necessary, though not strictly consistent with ASTM's Tier 1 definition. Because ASTM (1995) guidance was developed to focus smaller, more traditional UST sites (e.g., gasoline stations), predictive modeling to support Tier 1 NFRAP decisions was not suggested. However, many of the Air Force release sites are relatively large, involve multiple environmental media, and sometimes complex regulatory requirements (e.g., due to IRP designations or BRAC actions). Therefore, at these types of sites it is prudent to use predictive tools to assess chemical fate as part of the Tier 1 evaluation process to satisfy regulatory (and potentially public) concerns.

Appendix C (C.3 and C.4) summarize several simple equations that can be used to conservatively approximate predicted future site concentrations over time and distance at petroleum release sites. The results of the streamlined chemical fate assessment can then be compared to applicable RBSLs to determine whether additional remediation or evaluation is warranted to protect potential future (or downgradient) receptors. Appendix A presents a case study for Site OT-45 at Wurtsmith AFB, where a streamlined chemical fate assessment was completed as part of a NFRAP decision document.

D.2 CONDUCTING A MORE SITE-SPECIFIC (TIER 2) EVALUATION

The goal of the Tier 2 evaluation process, as defined in this handbook, is to establish health-protective site-specific target levels (SSTLs) based on data and assumptions about the likelihood and nature of exposure at a particular site. The impacts of natural chemical attenuation processes are more fully documented are also factored into the Tier 2 evaluation. A Tier 2 evaluation is more comprehensive than a Tier 1 evaluation, and requires additional data to complete a defensible quantitative exposure pathways analysis.

Although a Tier 2 evaluation could involve only minor modifications to the equations used to derive the RBSLs (such as possible adjustments suggested by the

ASTM RBCA framework), a Tier 2 evaluation for an Air Force petroleum release site typically requires use of more advanced models to predict the effect of natural chemical attenuation processes on exposure pathway completion and exposure-point concentrations over time.

D.2.1 Developing Site-Specific Target Levels

SSTLs are the focus of the Tier 2 evaluation. SSTLs are alternate cleanup objectives that, while land-use based, are more representative of site conditions than RBSLs. SSTLs differ from RBSLs in several ways:

- SSTLs incorporate site-specific data rather than generic assumptions about land and groundwater use restrictions;
- SSTLs are based on more reasonable exposure routes given the likelihood that reliable and enforceable exposure controls will limit/prevent certain types of receptor exposures to contaminated media;
- SSTLs account for the positive impacts of natural chemical attenuation processes on interrupting potential exposure pathways and/or minimizing exposure-point concentrations; and
- SSTLs may sometimes be based on higher (less conservative) target risk levels than RBSLs, once the decreased probability of actual exposure is documented.

SSTLs can be based on applicable RBSLs, with site-specific modifications, or SSTLs can be developed from new equations or derived from chemical fate assessment model results. Some states have specified the types of modifications, equations, and/or predictive models that can be used to conduct a Tier 2 evaluation (AAR, 1996). To ensure that the conclusions of the Tier 2 evaluation are understood by the regulatory authorities involved at a particular site, available guidance on what methods have been used or approved for use should be consulted. It is likely that the review and approval time for a Tier 2 evaluation could be substantially increased if an unfamiliar approach to quantifying exposure pathway completion and establishing SSTLs is employed.

This handbook recommends incorporating the procedures outlined in the AFCEE Intrinsic Remediation Technical Protocol (Wiedemeier *et al.*, 1995) to more fully document natural chemical attenuation. This approach generally represents an upgrade from the Tier 1 evaluation, where current contaminant concentrations are usually assumed to represent exposure-point concentrations or where typically simple calculations based on an assumed dilution/attenuation factor (DAF) are used to estimate natural chemical attenuation. In comparison, as part of a Tier 2 evaluation, site-specific data relevant to scientifically documenting field-scale evidence of natural chemical attenuation, especially biodegradation, of petroleum hydrocarbon compounds are collected. In this way, predictions about chemical fate over time and health-protective SSTLs are based on verifiable field evidence of natural chemical attenuation. This is an important component of the Air Force risk-based remediation strategy because:

- Field-scale evidence of natural chemical attenuation can be monitored over time to confirm the effectiveness of these processes at minimizing contaminant mass, persistence, mobility, and toxicity; and
- The timeframe for achieving various levels of risk-reduction can be estimated and factored into long-term land use decisions.

D.2.1.1 SSTLs for Human Receptors

SSTLs can be developed for potential human receptors using site-specific data and assumptions more representative of site conditions than the generic assumptions used to develop RBSLs. For example, the groundwater RBSL for an industrial site is likely based on the assumption that onsite workers ingest contaminated groundwater as their sole potable water source during the 8-hour workday. In comparison, the groundwater SSTL for an Air Force petroleum release site may be based on the site-specific assumption that only intrusive workers could come into direct contact with contaminated groundwater, and that the exposure route would be dermal contact rather than ingestion. Use of onsite groundwater as a potential potable water source may not be realistic given site conditions.

Figure D.1 illustrates how an SSTL can differ from an RBSL, and yet still provide the same level of protection (i.e., be based on similar target risk levels). Note that changing the assumption about how onsite industrial workers could be exposed to chemical contamination in groundwater significantly changes the target cleanup level. The assumptions used to develop the RBSLs should be reviewed to determine if they are representative of site conditions and reasonable exposure potential. A professional risk assessor should be consulted to establish credible SSTLs that are consistent with USEPA-recommended procedures. Technical guidance on developing SSTLs using site-specific exposure assumptions and defensible toxicity data is provided in USEPA (1991 and 1996) risk assessment documents, as well as in the manual for the RBCA computer program for the ASTM risk-based corrective action planning process (Groundwater Services, Inc., 1995).

In addition to modifying the SSTL to reflect actual receptor exposure potential, the impact of natural chemical attenuation processes on the mass of residual that can persist in onsite media and not present an unacceptable risk to potential receptors must be considered. This can be accomplished in two ways:

1. Chemical fate modeling results can be used to assess whether existing concentrations can migrate to potential exposure points at concentrations above the Tier 2 SSTLs. Typically, the primary difference between the Tier 1 and Tier 2 evaluation of natural chemical attenuation is the types of data used to estimate reductions in contaminant mass/toxicity over time (i.e., DAF approach versus site-specific, field-scale evidence). Recall from Section D.1.2., that an in-depth chemical fate and transport analysis is sometimes required even in the Tier 1 analysis.
2. Chemical fate modeling results also can be used to "back calculate" those concentrations that can remain onsite and not cause exceedances of Tier 2 SSTLs at the exposure-point. This approach can be applied if the chemical

FIGURE D.1

EXAMPLE DIFFERENCE BETWEEN INDUSTRIAL RBSL AND SSTL

Assuming Ingestion of Onsite Groundwater

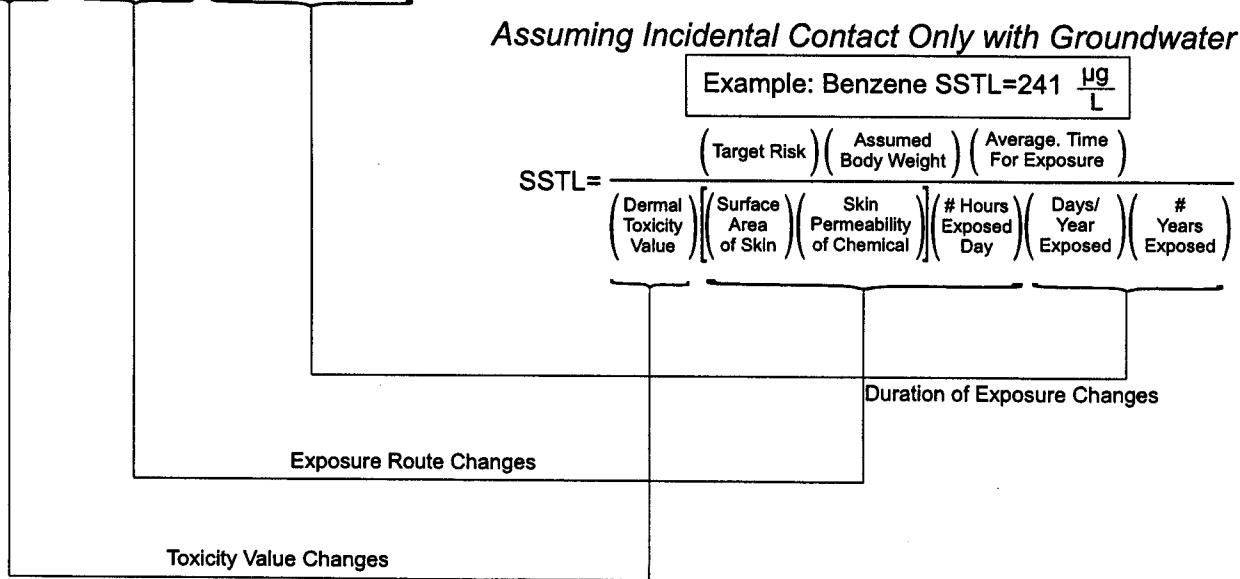
Example: Benzene RBSL=9.87 $\frac{\mu\text{g}}{\text{L}}$

$$\text{RBSL} = \frac{(\text{Target Risk}) (\text{Assumed Body Weight}) (\text{Average. Time For Exposure})}{(\text{Oral Toxicity Value}) (\text{Ingestion Rate Of Groundwater}) (\text{Days/Year Exposed}) (\text{\# Years Exposed})}$$

Assuming Incidental Contact Only with Groundwater

Example: Benzene SSTL=241 $\frac{\mu\text{g}}{\text{L}}$

$$\text{SSTL} = \frac{(\text{Target Risk}) (\text{Assumed Body Weight}) (\text{Average. Time For Exposure})}{(\text{Dermal Toxicity Value}) (\text{Surface Area of Skin}) (\text{Skin Permeability of Chemical}) (\text{\# Hours Exposed Day}) (\text{Days/Year Exposed}) (\text{\# Years Exposed})}$$



fate assessment is based on fairly simple estimation methods (Appendix C.3). For example, if the remediation goal is to prevent dissolved benzene contamination from exceeding SSTLs at the site boundary, a chemical fate assessment could be used to estimate how much benzene must be removed from the source area soils to enhance natural attenuation and ensure that SSTLs are not exceeded.

D.2.1.2 SSTLs for Ecological Receptors and Environmental Resources

SSTLs for the protection of ecological receptors usually are appropriate only at sites where special-concern species (e.g., threatened or endangered species) are at risk from exposure to site petroleum contaminants. In such instances, it is advisable to work closely with the appropriate resource trustees (e.g., the US Fish and Wildlife Service) to determine appropriate SSTLs for the specific species or population at risk. At most sites where ecological exposure pathways are completed, but where no special-concern species are present, it is appropriate to follow the same protocol used in the Tier 1 screening analysis, wherein the SSTL comparison conducted for human receptors, and the corrective actions selected based on the realities of the Tier 2 analysis, are assumed to be protective of ecological receptors exposed to the same media.

Where surface water quality is being or may in the future be degraded by site contamination, and in states that have promulgated surface water quality standards for protection of aquatic life, the state standards that were used as RBSLs may also become the SSTLs. However, at such sites it is important to carefully document the receptors present in the affected water body, and to note visible evidence of adverse effects (e.g., stressed vegetation along stream banks or absence of aquatic organisms that are present in unaffected portions of the same or similar nearby water bodies), or lack thereof. A qualitative discussion of the impacts of natural attenuation on chemicals in the surface water, based on differences in concentrations at the point of contaminant discharge and downstream from the site, also is important. Natural processes such as volatilization, dilution, and photo-oxidation can rapidly reduce site contaminant concentrations below aquatic life RBSLs/SSTLs, making corrective action to address surface water contamination unnecessary. Appendix E presents the case study for a site at Myrtle Beach AFB where state surface water criteria were used as RBSLs, and a discussion of receptors, relative habitat quality in affected portions of the surface water body, and natural attenuation processes acting on site chemicals discharging from groundwater seeps into the surface water was presented in lieu of a Tier 2 SSTL analysis for aquatic receptors. This discussion was used to support selection of a corrective action for groundwater that also is protective of surface water receptors.

In the rare instances where it is necessary to develop SSTLs for ecological receptors, a risk assessor can calculate such values for the various affected media to which receptors are exposed by using literature toxicity data to develop safe chemical- and matrix-specific concentrations that are appropriate to the predominant exposure routes involved. For example, exposure concentrations based on chemical properties (e.g., bioavailability) and behavioral characteristics of the affected receptors can be estimated using simple bio-uptake models and exposure models based on rates of ingestion and foraging ranges of the subject species. *However, this step is rarely required, and should not be undertaken unless expressly requested by the regulators involved.*

In many cases, the need to minimize continuing degradation of groundwater quality (i.e., prevent increases in plume core concentrations, eliminate increases in plume size) will define remedial requirements. These types of environmental impacts may not pose an unacceptable risk to potential receptors, but are contrary to the spirit and intent of the NCP and the Air Force's environmental protection policy. Appendix A presents the Site ST-27 case study from Charleston AFB, which illustrates how SSTLs that prevent additional degradation of groundwater resources were estimated using a simple model. Briefly, the source term for both the soil leaching and groundwater transport predictive models was **iteratively** adjusted after calibration until no further increases in plume concentration or size were predicted. Essentially, the models were used to develop a mass balance in the environmental media. The resulting SSTL was equivalent to that source contribution that could be attenuated by natural physical, chemical, and biological processes at the site. A similar approach could be undertaken to prevent further degradation of surface water or wetland resources that are receiving contaminated discharge from the site.

D.2.2 Developing a Limited Exposure Pathways Risk Analysis

Tier 2 evaluations are typically focused on the development of SSTLs, which are used to determine the potential risks and risk-reduction requirements at a particular site. Another method to characterize risk is available, however. In contrast to SSTLs, which define the residual level of contamination that can persist in onsite media without posing an unacceptable threat (i.e., above the target risk level), a limited exposure pathways risk assessment can be used to characterize the *cumulative risk* associated with exposure to existing concentrations of detected chemicals in all environmental media at the site (recall that SSTLs correspond to a target risk level for a single contaminant in a single medium). This approach estimates potential risk from all chemicals across all exposure pathways for individual receptors. Because cumulative risk estimates are provided via the BRA, the target risk level that may prompt some type of active remediation may be significantly higher (less stringent) than that used to develop SSTLs.

This alternative approach may be suitable for application at sites where CERCLA hazardous substances are associated with the petroleum contamination at a site, but not at significant concentrations that prompt remediation under CERCLA. This method of risk analysis is generally analogous to that traditionally required at RCRA and CERCLA sites to characterize baseline risks. However, there are some key distinctions between these two risk analysis methods. First, only reasonable exposure pathways that are or may be completed are considered in a limited exposure pathways risk analysis. In contrast, a more conventional baseline risk assessment (BRA) may include hypothetical exposure pathways that have an extremely low probability of being completed. Second, a limited exposure pathways risk analysis accounts for the positive impact of natural chemical attenuation processes on chemical mass and toxicity over time. This means that the exposure-point concentrations change over time, and this is accounted for in the risk estimate. Typically in the conventional BRA, steady-state concentrations are assumed, and predictive modeling results are rarely used to establish an exposure-point concentration that changes over time. Rather, site analytical data are used to develop baseline exposure-point concentrations, which are assumed to remain constant for the entire duration of receptor exposure (e.g., up to 25 years for an industrial worker).

In summary, this handbook recommends that a focused BRA only be performed when required by state guidance or regulations, or when the BRA can help support no further action. Otherwise, the simpler tiered approach is adequate to demonstrate risks from a particular site and much less resource intensive than the BRA approach. Although this alternate risk analysis method provides valuable insight as to the cumulative risk potential of chemical contamination at a site, SSTLs may still have to be developed to guide decisions on how best to reduce unacceptable risks. Matrix-specific, chemical-specific cleanup criteria can be used to evaluate the potential cost-effectiveness of various remedial approaches at achieving the desired level of risk reduction. SSTLs also are convenient matrix-specific endpoints that can be easily monitored to assess progress toward risk-reduction over time. To assess progress toward the desired level of risk reduction without SSTLs, a revised limited exposure pathways risk analysis would have to be developed for each new set of sampling data. Compliance costs associated with analysis of monitoring data could quickly become burdensome, particularly at complex sites with detections of multiple petroleum hydrocarbon compounds. Appendix A presents the case study for Site ST-14 at Carswell AFB, where both a limited exposure pathways risk analysis and SSTLs were used to assess site-specific risk reduction requirements.

D.3 CONDUCTING A MORE COMPLEX (TIER 3) EVALUATION

A more complex Tier 3 evaluation may be warranted if the Tier 2 evaluation indicates that the SSTLs cannot be achieved in a reasonable time frame or at reasonable cost using the primary remedial approaches and technologies. A Tier 3 evaluation, as defined as part of the Air Force risk-based remediation strategy, should only be conducted for sites where:

- A quantitative risk assessment using sophisticated modeling (e.g., Monte Carlo simulations) is necessary to define potential site risks with minimal uncertainty;
- More restrictive land and/or groundwater use controls would have to be enforced to prevent unacceptable exposure; and
- Conventional containment or isolation remedial technologies (e.g., pump and treat, leachate recovery, or slurry walls) are required to minimize or interrupt potentially significant exposure pathways.

Tier 3 evaluations will rarely be required for Air Force petroleum release sites, and are more likely at mixed-waste sites where soil or groundwater has the potential to contact human or ecological receptors.

Usually, site-specific data about how receptors could come into contact with contaminated media and how petroleum hydrocarbon compounds are attenuating in site media will be more than sufficient to establish appropriately protective risk-reduction requirements.

APPENDIX E

REMEDICATION TIME AND COST ESTIMATES AND RECOMMENDED PILOT TESTING

Appendix E provides a useful guide for estimating the timeframe and cost of several remediation technologies. Two screening criteria are presented: the estimated time and the estimated cost to achieve a required reduction in BTEX concentrations in the soil or groundwater. *The actual cleanup time and cost will be site-specific.* The purpose of Appendix E is to provide general guidance, not to replace professional judgment and a more rigorous comparison of the alternatives based on site-specific factors such as the initial concentration of BTEX and the relative difficulty of working at different sites or different regulatory environments. These cost estimates are based upon professional experience, and that same experience has made it clear that it is difficult to estimate time and cost without evaluating many factors. Site-specific cost and cleanup times should be professionally estimated before initiating a costly remediation program.

A series of cost charts are provided in Appendix E for general technology evaluations and project estimating for remedial technologies frequently used for petroleum contamination. These costs are all for BTEX contamination in moderately permeable soils, and assume good conditions for application of the technology. Lower-permeability soils will typically result in higher costs and slower cleanup times. Application to heavier hydrocarbons such as PAHs will usually result in longer time frames and higher costs. These are typical costs for DoD sites using standard technology installations, not high-priced research projects. These costs are based on actual costs incurred on AFCEE technology demonstration projects and the author's experiences with the application of the subject technologies under a variety of site conditions. The time and cost estimates assume the project is implemented to the minimum technical specifications to meet the risk-reduction objectives.

E1 HYPOTHETICAL SITE EXAMPLE

To illustrate the process of evaluating time and cost for different technologies a hypothetical fuel site is provided as an example. Assuming the following site conditions:

- 10,000-gallon (6,250 pound) spill;
- Silty sand, 20 feet to groundwater;
- Groundwater seepage velocity of 300 feet per year and an effective porosity of 0.3;
- A stable dissolved plume 50 feet wide, 200 feet long, and 5 feet thick;

- Maximum dissolved hydrocarbon concentration of 3 mg/L, and an average concentration of 1.0 mg/L;
- Unsaturated contaminated soil volume of about 2000 yd³;
- Maximum unsaturated soil concentration of 20,000 mg/kg, and an average of 1,000 mg/kg;
- Saturated- and smear-zone contaminated volume of about 100 yd³; and
- A maximum saturated soil concentration of 50,000 mg/kg, and an average of 4,000 mg/kg.

Using these data, we can estimate the following contaminant distribution:

- Dissolved mass = 50 ft x 200 ft x 5 ft x .3 x 28 L/ft³ x 1 mg/L
= 420,000 mg or 1 lb dissolved in groundwater,
- Mass in vadose soils = 2,000 yd³ x 2,600 lb/yd³ x 1,000 mg/kg x 10⁻⁶ (mg/kg)/(lb/lb)
= 5,200 lbs, and
- Mass in smear zone/saturated soils = 100 yd³ x 2,600 lb/yd³ x 4,000 mg/kg x 10⁻⁶ (mg/kg)(lb/lb)
= 1,040 lbs.

Based on leaching calculations discussed in Appendix C and a Bioplume II model simulation of source reduction, assume a 90-percent overall dissolved BTEX reduction is desired to achieve industrial groundwater RBSLs. Using Figures E.1 through E.6 for the 10,000 ft² groundwater plume, we can estimate the following:

Natural Attenuation,

Capital cost	\$25,000
Annual O & M @ \$250,000 for 20 yr, 7% present worth factor	<u>\$265,000</u>
Total Cost.....	\$290,000

Air Sparging

Capital cost	\$120,000
Annual O & M @ \$60,000 for 3 yr, 7% present worth factor	<u>\$157,000</u>
Total cost.....	\$277,000

Pump and Treat

Capital cost	\$350,000
Annual O & M @ \$180,000 for 10 yr, 7% present worth factor	<u>\$1,200,000</u>
Total cost.....	\$1,550,000

FIGURE E.1

APPROXIMATE CAPITAL COST FOR A BTEX REMEDIATION IN GROUNDWATER
(ASSUMES MODERATELY PERMEABLE SOILS, GOOD CONDITIONS)

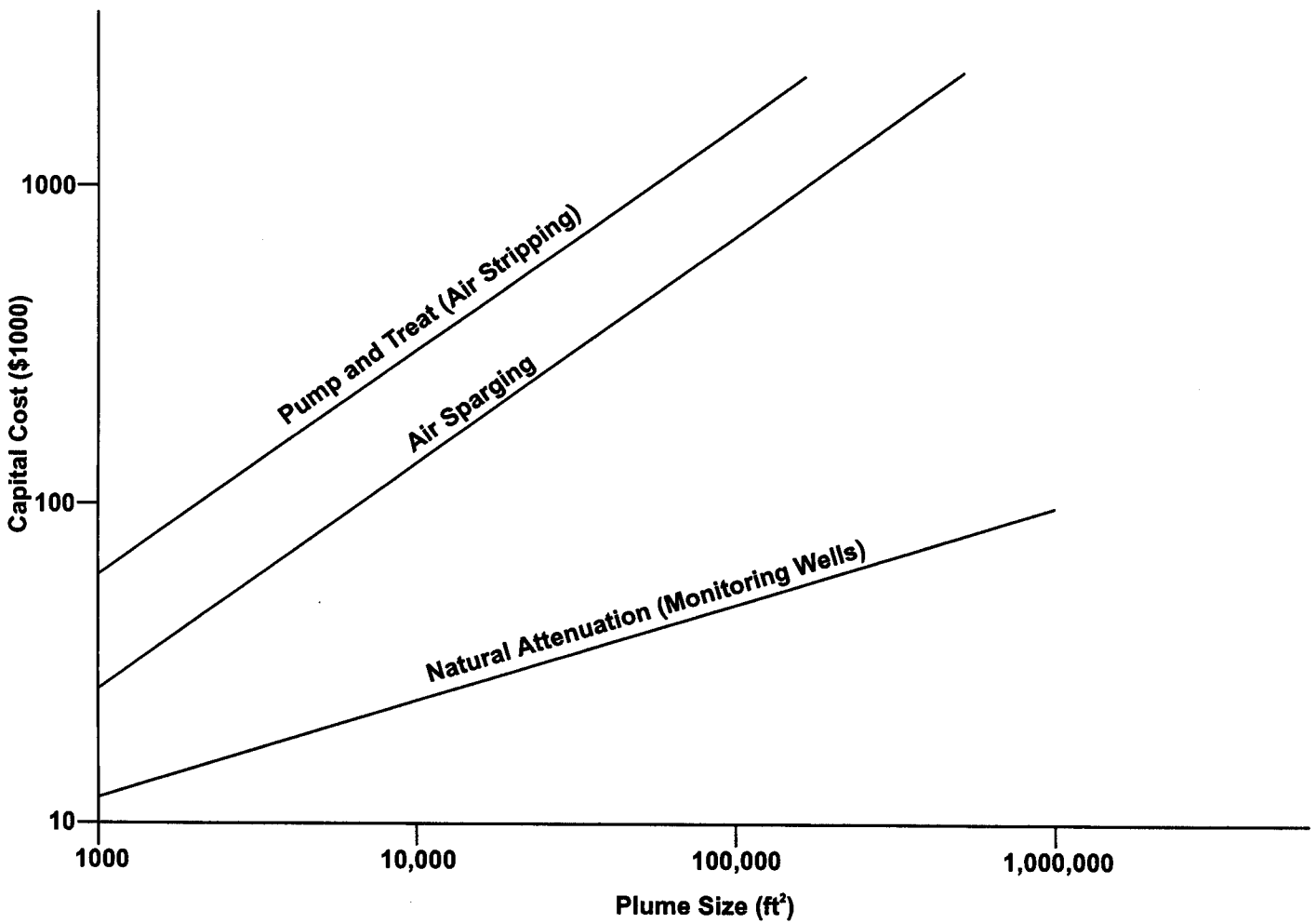


FIGURE E.2

APPROXIMATE OPERATION AND MAINTENANCE COST FOR
DISSOLVED BTEX IN GROUNDWATER
(ASSUMES MODERATELY PERMEABLE SOILS, GOOD CONDITIONS)

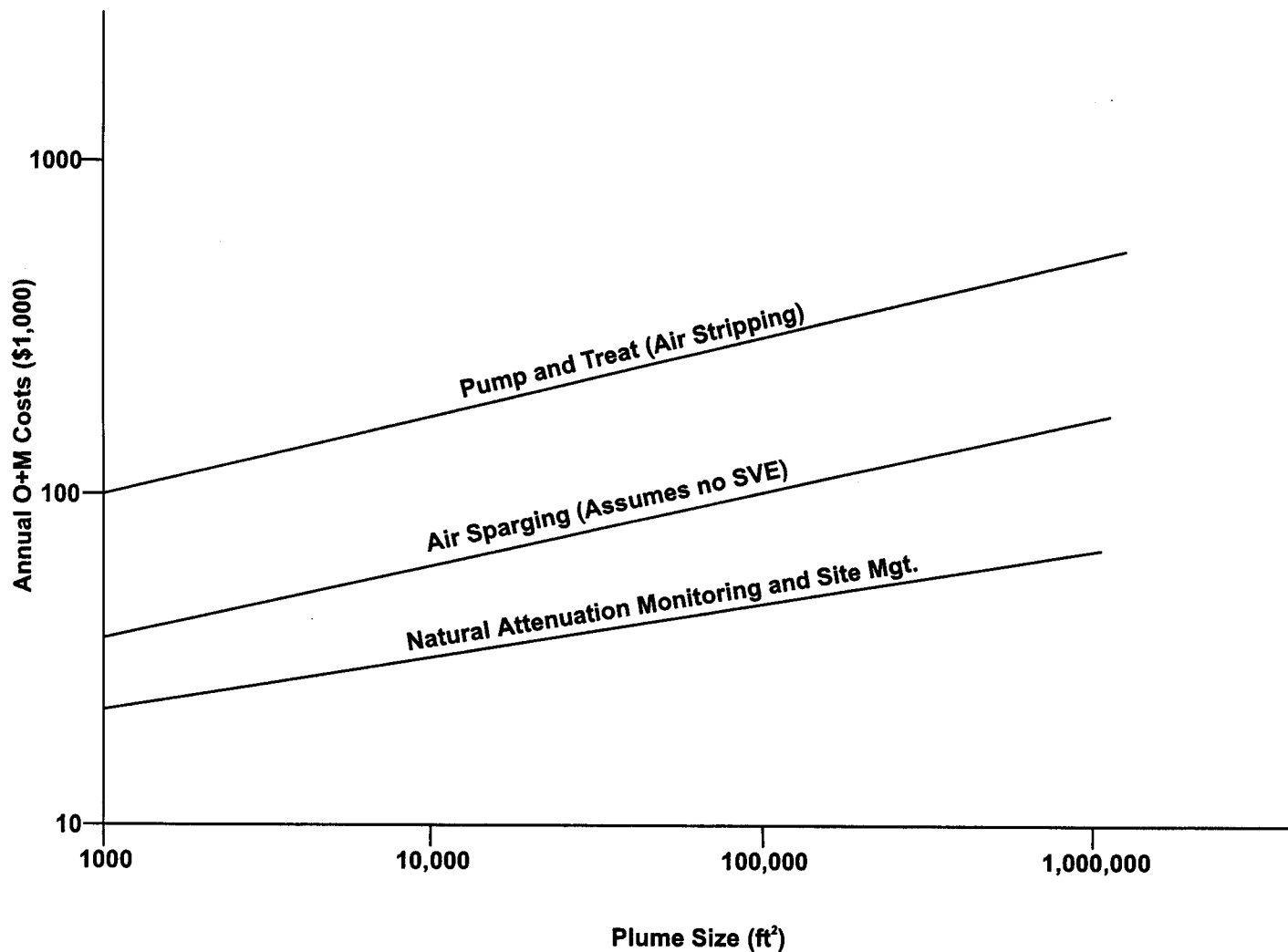


FIGURE E.3

**APPROXIMATE TIME REQUIRED FOR DISSOLVED
BTEX REMOVAL FROM GROUNDWATER
(ASSUMED MODERATELY PERMEABLE SOILS, GOOD CONDITIONS)**

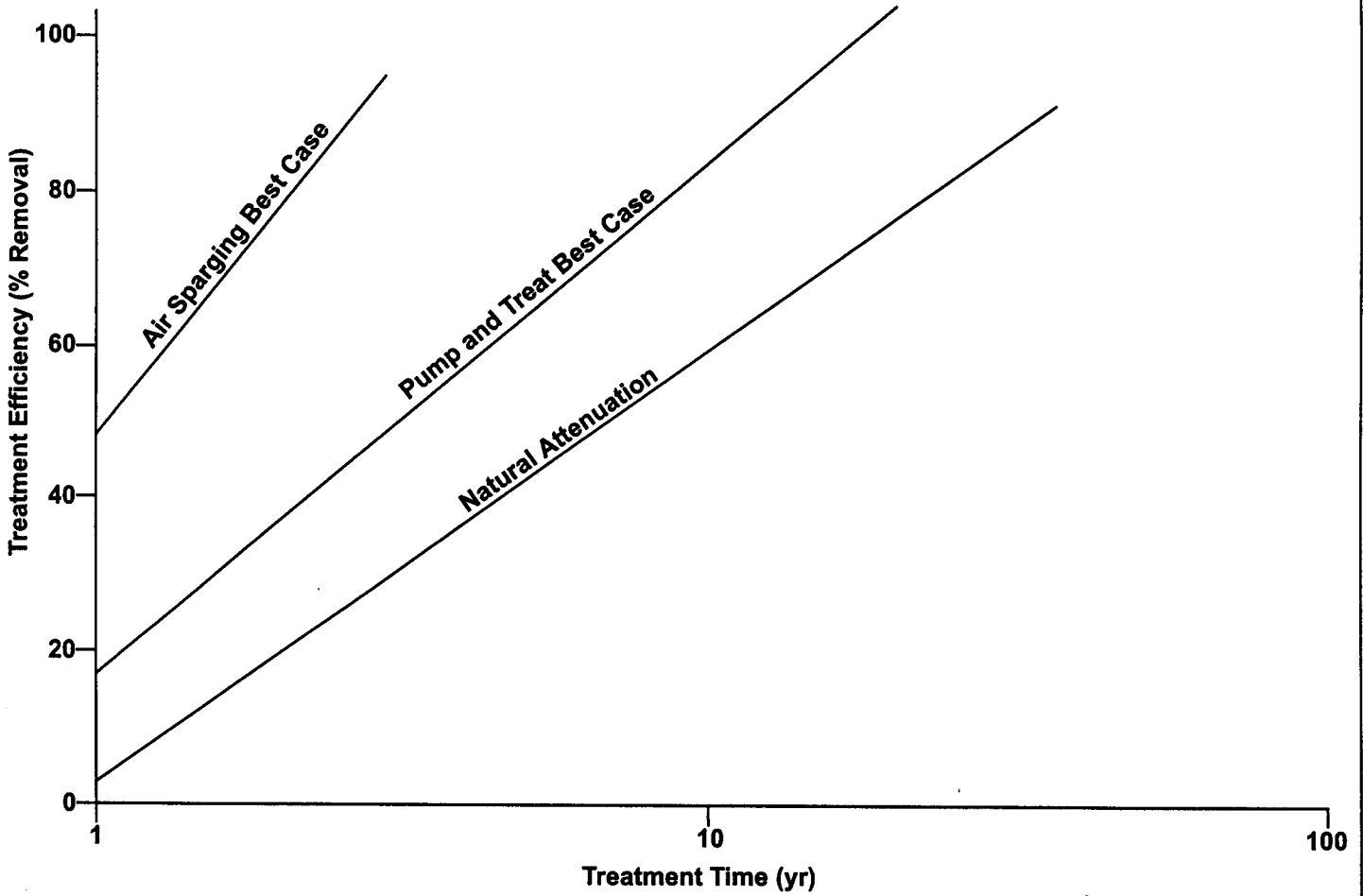


FIGURE E.4

**APPROXIMATE CAPITAL COST FOR REMEDIATION OF
SOILS CONTAMINATED WITH BTEX IN A HYDROCARBON MATRIX
(ASSUMED MODERATELY PERMEABLE SOILS, GOOD CONDITIONS)**

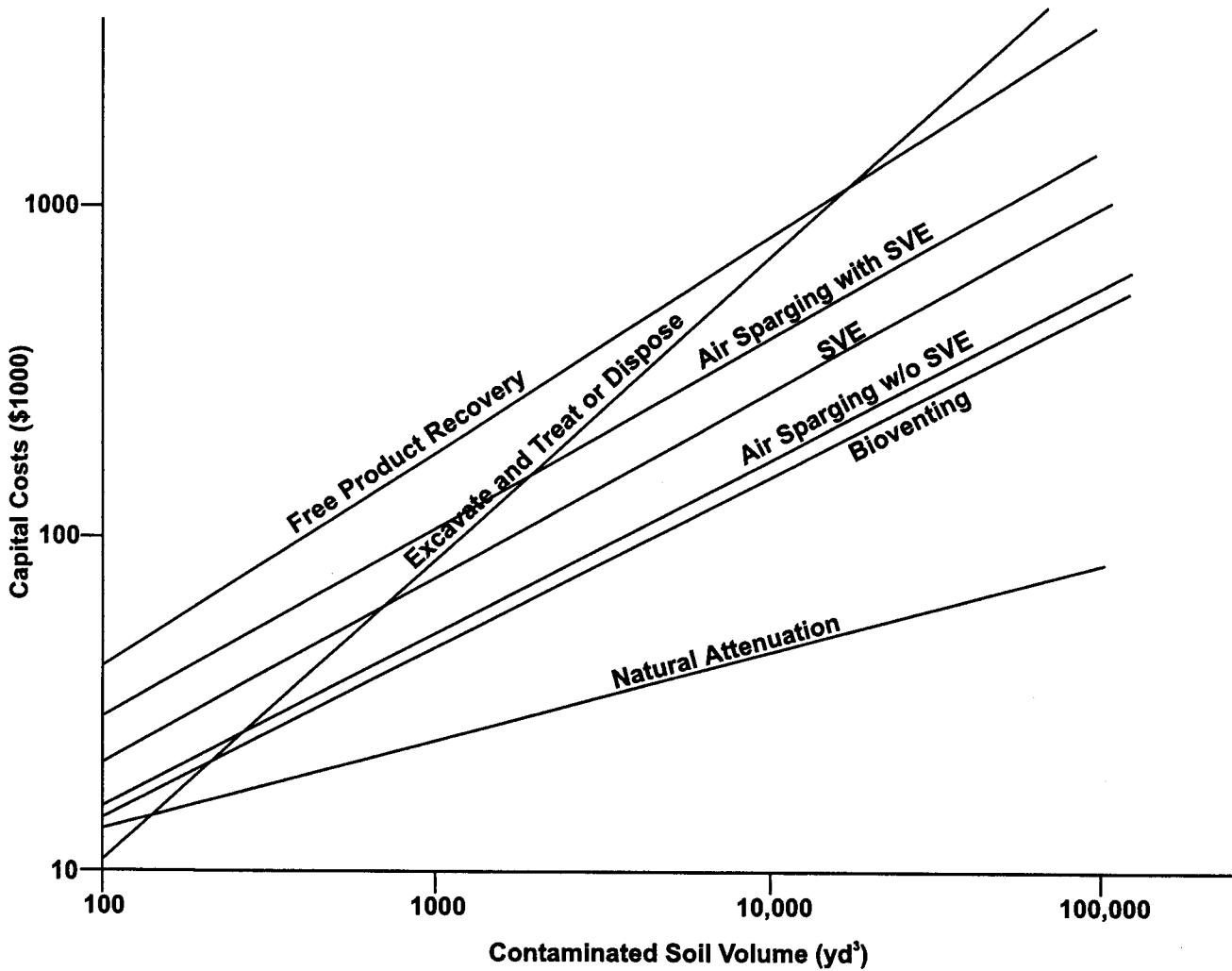


FIGURE E.5

**ANNUAL OPERATIONS AND MAINTANCE COST FOR REMEDIATION OF SOILS
CONTAMINATED WITH BTEX IN A HYDROCARBON MATRIX
(ASSUMED MODERATELY PERMEABLE SOILS, GOOD CONDITIONS)**

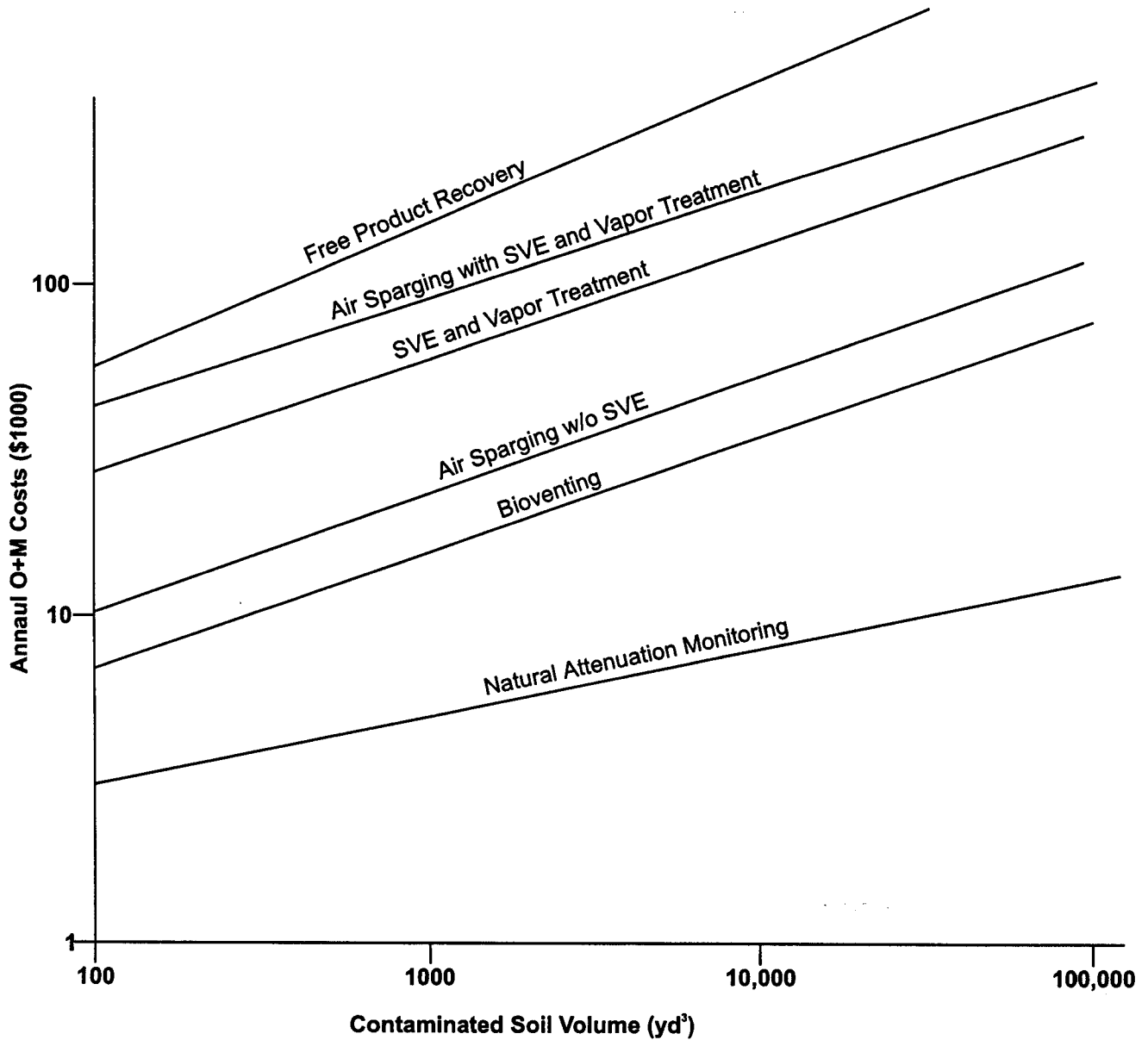
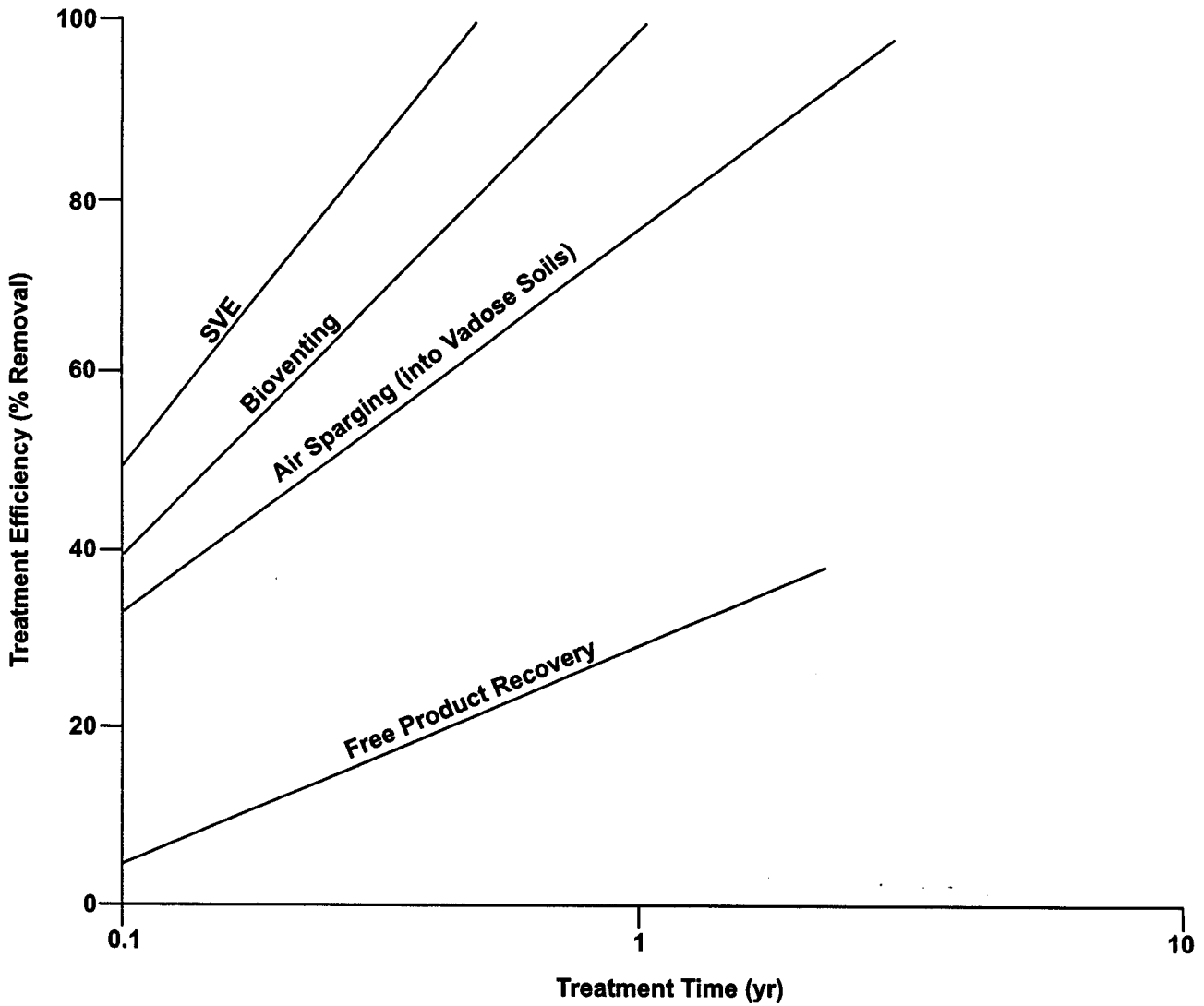


FIGURE E.6

**APPROXIMATE TIME REQUIRED FOR REMEDIATION OF
SOILS CONTAMINATED WITH BTEX IN A HYDROCARBON MATRIX
(ASSUMES MODERATELY PERMEABLE SOILS, GOOD CONDITIONS)**



As can be seen, the air sparging option has the lowest cost, and appears that it could achieve risk-based cleanup goals significantly sooner than natural attenuation alone. This initial cost estimate would be followed with a more detailed cost estimate to refine the costs of the natural attenuation and air sparging alternatives. It must be remembered however that air sparging is not as reliable as natural attenuation, and a pilot test would have to be completed to determine if air sparging could uniformly remove VOCs and add oxygen to this site. (The potential benefits of air sparging are great enough to justify a pilot test.) A similar evaluation process can be followed for soil treatment.

E.2 PILOT TESTING

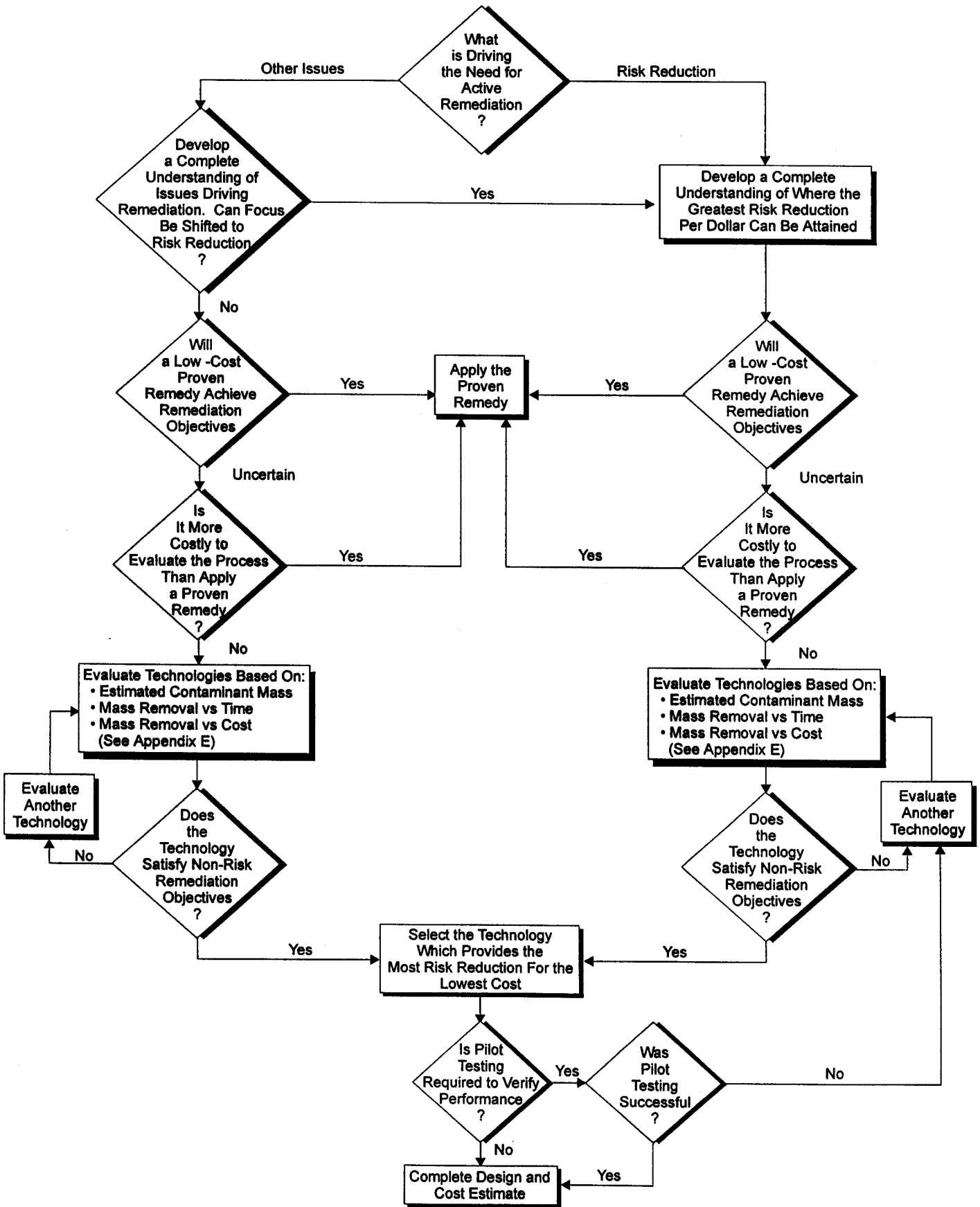
Pilot testing can serve two valuable functions in the technology selection and design process (Figure E.7). The first function is to confirm that a presumptive remedy such as bioventing will perform as expected at a specific site. Although technologies such as bioventing have achieved a 95-percent success rate at fuel-contaminated sites, there have been exceptions (e.g., several desert sites and wet clay sites) where bioventing was infeasible. If your site falls into one of these exception categories, a bioventing pilot test is strongly recommended.

A second function of a pilot test is to collect key performance data so that a full-scale system can be properly designed and installed. This is most important at larger sites where multiple wells or monitoring points must be properly spaced, and blower units must be properly sized. As with other steps in the process, the cost of the pilot test must be compared to the cost and additional unknowns of proceeding without site-specific test results. For example, at a small hydrocarbon site it may be more cost effective to simply install a one- or two-well bioventing system than to conduct a pilot test and then return to add an additional vent well. The cost of pilot testing can be significantly reduced if the testing can take place at the same time the risk-based site investigation is underway.

E.3.1 Combining Pilot Testing with Site Investigations

There are several simple tests that can be performed during the site investigation and used to establish the feasibility of the preferred technologies listed in Table E.1. As discussed in Appendix B, whenever a boring or probe is advanced, the field geologist/engineer should consider how that location could be used to collect pilot test information, natural attenuation data, or to prepare the site for a full-scale source reduction technology. Soil borings completed in contaminated soil should be completed as bioventing/SVE venting wells or soil vapor monitoring points. Soil borings completed in clean soil should be completed as background soil vapor monitoring points. Penetrations below the water table should be completed as either permanent or temporary monitoring wells for collecting contaminant or geochemical data. At least one well should be completed in the source area where free product is expected. This well can be used for product baildown testing.

FIGURE E.7
FLOW CHART FOR REMEDIATION TECHNOLOGY SELECTION



**Table E.1
Technologies for Remediation of Petroleum-Contaminated Sites**

Treatment Technology	Soils-Vadose	Soils-Smear	Soils-Saturated	Ground-water	Soil gas
In Situ					
Natural Attenuation	1	1	1	1	1
Bioventing	2	2	6	6	3
Soil Vapor Extraction	3	3	6	6	2
In Situ Heating Methods	3	3	6	6	4
Air Sparging/Bioventing	3	3	4	4,5	4
Biological Enhancements	4	4	4	4	6
In-Well Aeration/Recirculation	8	4	4	4	6
Barrier/Treatment Walls	8	8	6	4	8
Pump and Treat	8	8	7	4, 5	8
Free Product Recovery					
Skimming	8	4	6	6	8
Groundwater Depression	8	4	6	5	8
Bioslurping	4	4	6	5	3
Excavation and Ex Situ Treatment/Disposal					
Biopile	3	3	3	6	3
Low-Temperature Thermal Desorption	3	3	3	6	6
Offsite Disposal	3	3	3	6	6

1. Technology of first choice, usually lowest cost and effective; a preferred remedy.
2. Technology of choice if natural attenuation cannot be applied; usually a preferred remedy.
3. Technology that may be selected if 1 or 2 cannot be applied; may be a preferred remedy.
4. Technology that will provide some treatment, effectiveness uncertain; not a preferred remedy.
5. Technology that may be effective for containment; not a preferred remedy.
6. Technology may provide limited treatment, but is not designed for this purpose, and the effectiveness is uncertain; not a preferred remedy.
7. No immediate impact is expected, long-term improvement may occur as a result of application; not a preferred remedy.
8. No impact anticipated; not a preferred remedy.

E.3.2 Pilot Testing Objective

This subsection provides a summary of the most important pilot test objectives for many of the technologies listed in Table E.1. The specific pilot testing procedures for these technologies can be found in the referenced protocols and technical literature.

Bioventing

- Measure initial soil gas TVH, oxygen (O₂), and carbon dioxide (CO₂).
- Determine biodegradation rate using an *in-situ* respiration test.
- Determine soil gas permeability.
- Estimate the radius of pressure influence or oxygen influence at a constant flow rate.
- Determine the air injection pressure at the vent well.
- Additional information on bioventing pilot testing can be found in the *AFCEE Test Plan and Technical Protocol for Field Treatability Testing For Bioventing*.

Soil Vapor Extraction

- Measure initial soil gas TVH, O₂, and CO₂.
- Determine soil gas permeability.
- Determine radius of vacuum influence for several flow rates
- Measure the vacuum at the venting well for each flow rate.
- Measure extracted soil gas TVH, O₂, CO₂, and BTEX compounds
- Additional information on SVE testing can be found in *A Practical Approach to the Design, Operation, and Monitoring of In Situ Soil-Venting Systems* (Johnson *et al.*, 1990).

Air Sparging

Pilot testing objectives for air sparging are more difficult to define than objectives for bioventing or SVE. There are many opinions as to which parameters should be monitored during an air sparging pilot test and how to interpret parameters. Listed below are a few of the more accepted test objectives.

- Measure the air injection pressure at the well which is required to inject 5 cfm of air/well.
- Measure water levels in monitoring wells to observe any mounding due to air displacement of groundwater.

- Measure the increase in DO in nearby monitoring wells. Short-screened (< 1 foot long) well points are useful for determining uniformity of oxygen distribution. If bubbling is observed in a monitoring well, it means that a large air channel has entered the well. DO data from this well will be unacceptable.
- If an SVE system is operating in the vadose zone, it should be monitored for an increase in VOCs when the sparging system is turned on.
- There is no single document that describes a standard air sparging pilot test. The reader is referred to Acomb *et al.* (1995), Marley *et al.* (1995), and Johnson *et al.* (1995) for additional insights on pilot testing techniques.

Pump and Treat

As discussed throughout this section, pump and treat technologies will seldom be required at fuel-contaminated sites, and should not be considered unless the dissolved contaminant plume has a high probability of contaminating a sole-source drinking water aquifer or other sensitive resource. In those instances, pump and treat may be an effective method of containing contaminant migration. *Groundwater Contamination - Optimal Capture and Contaminant* (Gorelick *et al.*, 1993). provides additional information on pilot testing and optimization of pump and treat systems. The aquifer tests described in Section B.7.4 can be completed during the site characterization.

Free Product Recovery

Regardless of the type of product recovery system that is selected, there are some basic tests that should be completed at each site:

- Measure free product thickness in each well to verify the extent of the LNAPL body.
- Complete a simple bail-down test in each well that contains at least 1 inch of mobile LNAPL to see how rapidly the product recovers. If it takes less than 1 day to recover to the initial free product thickness, there is probably enough recoverable product to justify a bioslurping pilot test.
- Additional information on bioslurping pilot testing can be found in the *AFCEE Test Plan and Technical Protocol for Bioslurping*.

Excavation and Treatment

- Can the soil be easily excavated without destroying expensive infrastructure?
- Estimate the total volume of contaminated soil.
- Is there an existing soil landfarm, biopile, or thermal system at or near the base?
- Determine if an air emissions permit or air monitoring (e.g., in the worker breathing zone) will be required during excavation or treatment.

- Determine the sand, silt, and clay content and percent moisture of the soil. This information will be needed to determine landfarming, biopile, or thermal treatment feasibility. Moist clays are difficult and more expensive to handle in any of these processes.

APPENDIX F

OVERVIEW OF APPLICABLE REGULATIONS

This appendix provides an overview of major regulatory programs their potential applicability to petroleum hydrocarbon remediation is presented in the first subsection. A brief overview of why and how the state underground storage tanks (UST) programs are changing to be more flexible and allow use of risk-based remediation strategies also is provided.

F.1 DETERMINING APPLICABLE REGULATIONS FOR YOUR SITE

Before developing a remediation plan for any petroleum hydrocarbon release site, it is important to first identify which environmental laws and regulations may apply to your particular site. For example, petroleum hydrocarbon contamination resulting from a UST release is most likely addressed under state and federal UST programs, which may already be structured to allow a risk-based remediation strategy. However, petroleum hydrocarbon contamination resulting from other types of releases, such as from an aboveground storage tank may be subject to other environmental regulations, which may require additional evaluation not included in the Air Force risk-based strategy presented in this handbook. This appendix contains a brief guide for determining the appropriate regulatory approach for remediation of your petroleum hydrocarbon release site. You are encouraged to confirm that your proposed regulatory approach is acceptable to the responsible regulatory agency(ies) *prior to initiating any remedial activities*. Your regulatory compliance strategy should also be coordinated and implemented in the context of your base management action plan (MAP).

F.1.1 What Laws and Regulations Must You Consider?

When remediating petroleum hydrocarbon release sites, the Air Force may have to meet the requirements of the following environmental laws and regulations:

- State and federal laws, regulations, and guidance for UST fuel storage and handling facilities or for their remediation;
- The Spill Prevention, Control, and Countermeasures (SPCC) program [Title 40 Code of Federal Regulations (CFR) Part 112] and the Oil Pollution Act;
- Section 120 of Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), as amended by the Superfund Amendments and Reauthorization Act (SARA), which establishes procedures for responding to releases of hazardous substances, pollutants, and contaminants into all media;

- Subtitle C of Resource Conservation and Recovery Act (RCRA), as amended by the Hazardous and Solid Waste Amendments of 1984 (HSWA); and/or
- Local permits and requirements for local zoning and planning boards.

Following is a list of the basic questions you should answer to determine which laws and regulations you may have to comply with when addressing petroleum hydrocarbon contamination at your particular site. Figure F.1 outlines the decision path you should follow to identify which laws and regulations you may have to consider when developing a remediation strategy for your site. In general, placing the site under the jurisdiction of a state UST program will be most compatible with the Air Force remediation approach because both programs have a risk-based corrective action decision as their final goal.

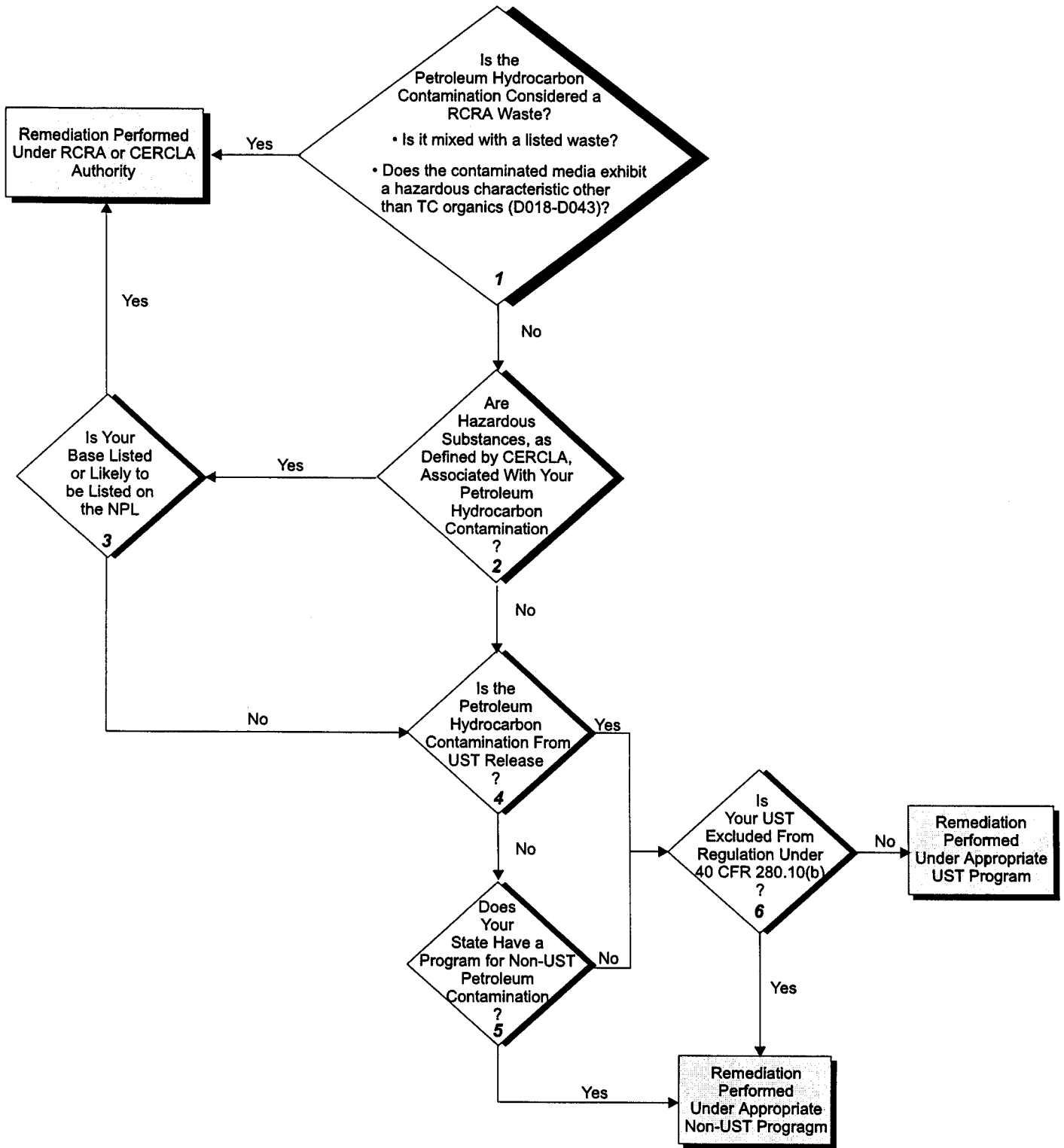
1. *Is the petroleum hydrocarbon contamination considered a RCRA hazardous waste?*

The soil and groundwater contamination at your site could be considered a RCRA hazardous waste if it exhibits a hazardous characteristic or if it is mixed with a listed hazardous waste. Hazardous characteristics include ignitability, corrosivity, reactivity, and toxicity. Listed hazardous wastes include spent chlorinated solvents and a long list of other types of wastes. The listed wastes are identified in 40 CFR Parts 261.31, 261.32, and 261.33.

Unless the petroleum is mixed with other types of contamination, the most likely hazardous characteristics the petroleum will exhibit is ignitability and/or toxicity. For example, if free product is present and the mixture of groundwater and free product has a flashpoint of less than 140°F, then that material is an ignitable waste. An example of a toxicity characteristic (TC) waste is lead, which is found occasionally in petroleum hydrocarbon contamination. However, for a waste to exhibit the TC of lead, there must be more than 5 milligrams per liter (mg/L) of lead in the TC leaching procedure (TCLP) extract of the sample. Lead is rarely measured at such concentrations in petroleum sources commonly used by the Air Force [e.g., jet fuel JP-4, jet fuel JP-8, motor gasoline (MOGAS), diesel fuel]. *USEPA has exempted petroleum-hydrocarbon-contaminated soils from classification as a TC waste for the TC organic constituents. This means that petroleum-contaminated soils cannot fail the test because of the presence of TC organic compounds such as benzene.* In fact, petroleum-contaminated environmental media and debris that fail only the TC for organics D018 through D043 and are subject to the corrective action requirements for USTs under 40 CFR 280 (see below) are exempt from RCRA (USEPA, 1993).

If the petroleum hydrocarbon contamination at your site meets the definition of a RCRA hazardous waste, you will have to comply with the generator, storage,

**FIGURE F.1
DETERMINING REGULATORY FRAMEWORK**



treatment, and disposal requirements under RCRA. However, based on experience at other Air Force petroleum hydrocarbon release sites, you will rarely determine that your petroleum contamination is a RCRA hazardous waste unless your petroleum was mixed with a listed hazardous waste prior to or after release.

2. *Are hazardous substances, as defined by CERCLA, associated with your petroleum hydrocarbon contamination?*

If the source of your petroleum hydrocarbon contamination is a UST (question 2) or if you are addressing petroleum contamination under a state or Air Force program (question 3), you need to determine whether hazardous substances, as defined by CERCLA, may be present in the contaminated soil or groundwater at your site. This question is different than question 1 about RCRA hazardous waste. Contaminated environmental media may contain hazardous substances and not be a RCRA hazardous waste.

The definition of *hazardous substances* [CERCLA Section 101(14)] specifically excludes "petroleum, including crude oil or any fraction thereof," unless specifically listed. There is no definition of *petroleum* in CERCLA. However, the USEPA (1987) has interpreted the petroleum exclusion provision to include gasoline, jet fuels, diesel fuels, etc. (fractions of crude oil), including the hazardous substances, such as benzene, that are commonly found in or indigenous to the petroleum substances. Because these hazardous substances are found naturally in all crude oil and its fractions, they are included in the term petroleum. The term also includes hazardous substances that are normally mixed with or added to crude oil fractions during the refining process, including hazardous substances whose levels are increased during refining. These substances also are part of petroleum because their addition is part of the normal oil separation and processing operations at refineries that produce the products commonly understood to be petroleum. However, hazardous substances that are added to petroleum or that increase in concentration solely as a result of contamination of the petroleum during use are not part of the petroleum and are not excluded from regulation under CERCLA (USEPA Memorandum from the Office of General Counsel concerning the Petroleum Exclusion, July 31, 1987).

If CERCLA hazardous substances, designated under Section 101(14) and listed in the Appendix to 49 CFR 172.101, are associated with petroleum contamination at your site, you may be required to address the remediation of the site under CERCLA. One common example of this is the past practice of adding chlorinated solvents to fuels for fire training exercises. In this case the fuel and solvent contaminated soil often is a CERCLA hazardous material. If you determine that hazardous substances are not associated with your petroleum release site, skip to question 6.

3. *Is your base listed or likely to be listed on the Superfund National Priorities List (NPL)?*

If you have determined that hazardous substances are associated with your petroleum release site and your base is currently, or is likely to be, listed on the

NPL, you will have to conduct the remediation of your site under CERCLA. You will probably need to consult several parties to complete this answer because there will be substantial implications for your remediation activities at your *hazardous substance* site if the base is listed on the NPL. The Air Force risk-based remediation strategy outlined in this handbook can be applied to CERCLA sites, but may require additional sampling and documentation to meet the requirements of CERCLA regulations and guidance.

If your base is not listed on the NPL and is not likely to be listed, you usually can proceed with remediation of your site under the applicable (state or federal) UST program. Because petroleum is excluded from the hazardous substance list (Appendix to 49 CFR 172.101), the key element for determining whether you can conduct remediation under a UST program will be the level and extent of non-petroleum hazardous substance contamination at your particular site.

4. *Is the petroleum hydrocarbon contamination from a UST release?*

If you determine that your petroleum is not a CERCLA hazardous substance (question 2), you next need to determine whether the petroleum hydrocarbon contamination is from a leaking UST system. Although this step may seem trivial, the implications for your regulatory strategy are not. If the petroleum contamination is associated with a UST, the waste is eligible for a specific exclusion under RCRA (40 CFR 261.4(b)(10)). The formal definition of a UST is a tank and its associated piping that has more than 10 percent of its capacity below ground surface (bgs). If your release is associated with a UST, skip to question 6.

5. *Does your state have a program for non-UST petroleum contamination?*

If you determine that the petroleum hydrocarbon contamination at your site is from a source other than a UST, any remediation plans may fall under the jurisdiction of a separate state program, such as a state water program, a separate oil contamination program, or a voluntary cleanup program. In most cases, the substantive requirements of these programs do not differ significantly from UST program requirements. The Air Force risk-based remediation approach can be easily tailored to meet the compliance requirements of these types of programs.

If your state does not have a non-UST petroleum program or equivalent, the Air Force policy is to pursue appropriate and voluntary remedial actions to prevent adverse impacts to human health and environmental resources in accordance with the intent and spirit of the National Contingency Plan (NCP). Any remedial activities associated with non-UST petroleum release sites that do not fall under the authority of state programs may best be addressed as part of the Defense Environmental Restoration Program (DERP).

6. *Is the UST excluded from regulation under 40 CFR 280.10(b)?*

The federal UST regulations define the types of USTs that are excluded from UST regulations. USTs that are formally excluded from UST regulation include:

- USTs that contain RCRA hazardous wastes (question 1);

- Equipment or machinery that contain regulated substances for operational purposes, such as hydraulic lift tanks;
- UST systems having capacities of less than 110 gallons; and
- Emergency or overflow UST systems that are expeditiously emptied after use.

If your source UST is exempt from the UST regulations, you may conduct remediation under an appropriate non-UST state program (e.g., voluntary cleanup programs) or under DERP. If your source UST is subject to UST regulations, you may complete remedial activities under the applicable state or federal UST program.

The Air Force risk-based remediation strategy for petroleum release sites can and should be applied regardless of the regulatory framework. Documentation requirements under RCRA and CERCLA are generally more cumbersome than state UST programs, so whenever possible, sites should be placed under the jurisdiction of state UST programs.

APPENDIX G

RECOMMENDED REFERENCES AND POINTS OF CONTACT

GENERAL REFERENCES ON RISK-BASED REMEDIATION

- American Society for Testing and Materials (ASTM), 1994. *Emergency Standard Guide for Risk-Based Corrective Action Applied at Petroleum Release Sites*, ES 38-94. **Contact:** American Society of Testing and Materials, 1916 Race St. Philadelphia, PA. Zip 19103, Phone:
- Groundwater Services, Inc., 1995. Tier 2 Guidance Manual for Risk-Based Corrective Action. Houston, TX. **Contact:** Groundwater Services Inc., 5252 Westchester, Suite 270, Houston, TX, Zip 77005, Phone: (713) 666-1734.
- American Assoc. of Railroads. 1996. A Survey of State's Approaches to Risk-Based Corrective Action. Environmental Engineering and Operations Working Committee. February.

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- USEPA Region III, 1995. Risk-Based Concentration Table, July-December. Memorandum from Roy L. Smith, Ph.D., Office of RCRA Technical & Program Support Branch (3HW70). October 20. **Contact:** USEPA-Region III, 841 Chestnut St., Philadelphia, PA. 19107, Phone: TBD.
- USEPA, 1996. Soil Screening Level Guidance. **Contact:** National Technical Information Service, US Dept. of Commerce, 5285 Port Royal Road, Springfield, VA. 22161 Phone: (703) 487-4650.
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