United States
Environmental Protection
Agency

Office of Research and
Development
Washington, DC 20460

EPA/540/R-95/534a
September 1995

Manual

Bioventing Principles and Practice

Volume I: Bioventing Principles

EPA/540/R-95/534a
September 1995

Manual

Principles and Practices of Bioventing
Volume I: Bioventing Principles

U.S. Air Force Environics
Directorate of the
Armstrong Laboratory
Tyndall AFB, FL

U.S. Air Force Center for
Environmental Excellence
Technology Transfer Division
Brooks AFB, TX

U.S. Environmental Protection Agency
Office of Research and Development
National Risk Management Research Laboratory
Center for Environmental Research Information
Cincinnati, Ohio

Notice

The information in this document has been funded wholly, or in part, by the U.S. Environmental Protection Agency (EPA). This document has been subjected to EPA's peer and administrative review and has been approved for publication as an EPA document. The methods presented in this document are ones often used by the U.S. Air Force and EPA but are not necessarily the only methods available. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

This document is equivalent to U.S. Air Force document AL/EQ-TR-1995-0037.

Contents

Contents (continued)

Figures

Figure **Page**

Figures (continued)

Figure **Page**

Tables

List of Examples

List of Symbols and Acronyms

AFB	Air Force Base
AFCEE	U.S. Air Force Center for Environmental Excellence
AL/EQ	Armstrong Laboratory Environics Directorate
ANGB	Air National Guard Base
AVGAS	aviation gas
BTEX	benzene, toluene, ethylbenzene, and xylenes
cfm	cubic feet per minute
DNAPL	dense nonaqueous phase liquid
EPA	U.S. Environmental Protection Agency
LNAPL	less dense nonaqueous phase liquid
NAS	Naval Air Station
NLIN	nonlinear regression procedure
PAH	polycyclic aromatic hydrocarbon
PCB	polychlorinated biphenyl
RD&A	Research, Development, and Acquisition
SAS	Statistical Analysis System
SVE	soil vacuum extraction
TCE	trichloroethylene
TKN	total Kjeldahl nitrogen
TPH	total petroleum hydrocarbon
TVH	total volatile hydrocarbon
UST	underground storage tank
VOC	volatile organic carbon
C_S	quantity sorbed to the solid matrix
C_V	volumetric concentration in the vapor phase
C_{vsat}	saturated vapor concentration
C_W	volumetric concentration in the aqueous phase
E_a	activation energy
f_{oc}	organic carbon fraction
k	maximum rate of substrate utilization
k_d	endogenous respiration rate
k_o	baseline biodegradation rate
k_B	biodegradation rate
K_d	sorption coefficient
K_{ow}	octanol/water partition coefficient
K_S	Monod half-velocity constant
k_T	temperature-corrected biodegradation rate
MW	molecular weight
P_V	vapor pressure of pure contaminant at temperature T
R	gas constant
R_I	radius of influence
S	concentration of the primary substrate (contaminant)
s_x	solubility in water
t	time
T_{abs}	absolute temperature (°K)
χ	mole fraction
X	concentration of microorganisms
Y	cell yield

Conversion Factors

To convert . . .	to . . .	**multiply by . . .**
cubic feet	cubic meters	0.02831685
cubic feet	liters	0.03531
cubic inches	cubic centimeters	610.2
cubic yards (tons)	cubic meters	0.7646
cubic yards (tons)	kilograms	907.1843
darcy	square centimeter	9.869233×10^{-9}
darcy	square meter	9.869233×10^{-13}
degrees Fahrenheit	degrees Celsius	$t_{°C} = (t_{°F} - 32)/1.8$
degrees Fahrenheit	degrees Kelvin	$t_{°K} = (t_{°F} - 523.67)/1.8$
feet	meters	0.3048
horsepower	kilowatts	0.7457
inches	centimeters	2.54
kilocalories	joules	4,186.8
millimeters of mercury (°C)	Pascals	133.322
parts per million	milligrams per liter	1
parts per million	grams per liter	1,000
pounds	kilograms	0.45354237
pounds per square inch	kiloPascals	6.895
square inches	square centimeters	6.4516
tons	metric tons	0.90718474
U.S. gallons	liters	3.785

Acknowledgments

This manual was prepared by Andrea Leeson and Robert Hinchee of Battelle Memorial Institute, Columbus, Ohio, for the U.S. Environmental Protection Agency's (EPA's) National Risk Management Research Laboratory, Cincinnati, Ohio; the U.S. Air Force Environics Directorate of the Armstrong Laboratory, Tyndall AFB, Florida; and the U.S. Air Force Center for Environmental Excellence, Technology Transfer Division, Brooks AFB, Texas.

The project managers for this manual were Lt. Colonel Ross Miller, U.S. Air Force Center for Environmental Excellence; Gregory Sayles, EPA National Risk Management Research Laboratory; and Catherine Vogel, U.S. Air Force Environics Directorate, Armstrong Laboratory. These individuals also contributed to the content of the manual.

The manual was peer reviewed by:

Ryan Dupont, Utah State University
Chi-Yuan Fan, U.S. EPA National Risk Management Research Laboratory
Paul Johnson, Arizona State University
Jack van Eyck, Delft Geotechnic

Acknowledgments are also given to the following individuals who contributed to this document:

Bruce Alleman, Battelle Memorial Institute
Douglas Downey, Parsons Engineering Science
Gregory Headington, Battelle Memorial Institute
Jeffrey Kittel, Battelle Memorial Institute
Priti Kumar, Battelle Memorial Institute
Say Kee Ong, Iowa State University
Lawrence Smith, Battelle Memorial Institute

Eastern Research Group, Inc., Lexington, Massachusetts, copy edited and prepared camera-ready copy of this manual.

This document is a product of the bioventing research and development efforts sponsored by the U.S. Air Force Armstrong Laboratory, the Bioventing Initiative sponsored by the U.S. Air Force Center for Environmental Excellence (AFCEE) Technology Transfer Division, and the Bioremediation Field Initiative sponsored by the U.S. Environmental Protection Agency (EPA).

The Armstrong Laboratory Environics Directorate (AL/EQ), an element of the Air Force Human Systems Center, began its bioventing research and development program in 1988 with a study at Hill Air Force Base (AFB), Utah. Follow-up efforts included field research studies at Tyndall AFB, Florida; Eielson AFB, Alaska; and F.E. Warren AFB, Wyoming, to monitor and optimize process variables. The results of these research efforts led to the Bioventing Initiative and are discussed in this document.

The AFCEE's Bioventing Initiative has involved conducting field treatability studies to evaluate bioventing feasibility at over 125 sites throughout the United States. At those sites where feasibility studies produced positive results, pilot-scale bioventing systems were installed and operated for 1 year. Results from these pilot-scale studies culminated in the production of this document.

EPA's Bioremediation Field Initiative was established to provide EPA and state project managers, consulting engineers, and industry with timely information regarding new developments in the application of bioremediation at hazardous waste sites. This program has sponsored field research to enable EPA laboratories to more fully document newly developing bioremediation technologies. As part of the EPA Bioremediation Field Initiative, EPA has contributed to the Air Force Bioventing Initiative in the development of the test plan for conducting the pilot-scale bioventing studies and assisted in the development of this manual.

The results from bioventing research and development efforts and from the pilot-scale bioventing systems have been used to produce this two-volume manual. Although this design manual has been written based on extensive experience with petroleum hydrocarbons (and thus, many examples use this contaminant), the concepts here should be applicable to any aerobically biodegradable compound. The manual provides details on bioventing principles; site characterization; field treatability studies; system design, installation, and operation; process monitoring; site closure; and optional technologies to combine with bioventing if warranted. This first volume describes basic principles of bioventing. The second volume focuses on bioventing design and process monitoring.

Chapter 1
Introduction

Bioventing is the process of aerating soils to stimulate in situ biological activity and promote bioremediation. Bioventing typically is applied in situ to the vadose zone and is applicable to any chemical that can be aerobically biodegraded but to date has primarily been implemented at petroleum-contaminated sites. Through the efforts of the U.S. Air Force Bioventing Initiative and the U.S. EPA Bioremediation Field Initiative, bioventing has been implemented at over 150 sites and has emerged as one of the most cost-effective, efficient technologies currently available for vadose zone remediation of petroleum-contaminated sites. This document is a culmination of the experience gained from these sites and provides specific guidelines on the principles and practices of bioventing.

Much of the hydrocarbon residue at a fuel-contaminated site is found in the vadose zone soils, in the capillary fringe, and immediately below the water table (Figure 1-1). Seasonal water table fluctuations typically spread residues in the area immediately above and below the water table. In the past, conventional physical treatment involved pump and treat systems, where ground water was pumped out of the ground, treated, then either discharged or reinjected. Although useful for preventing continued migration of contaminants, these systems rarely achieved typical cleanup goals. Bioventing systems are designed to remove the contaminant source in the vadose zone, thereby preventing future and/or continued contamination of the ground water.

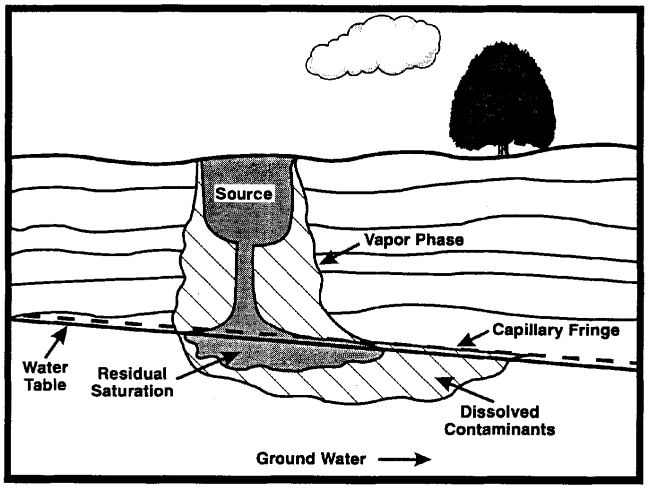


Figure 1-1. Hydrocarbon distribution at a contaminated site.

A typical bioventing system is illustrated in Figure 1-2. Although bioventing is related to the process of soil vacuum extraction (SVE), these processes have different primary objectives. SVE is designed and operated to maximize the volatilization of low-molecular-weight compounds, with some biodegradation occurring. In contrast, bioventing is designed to maximize biodegradation of aerobically biodegradable compounds, regardless of their molecular weight, with some volatilization occurring. The major distinction between these technologies is that the objective of SVE (also called soil venting) is to optimize removal by volatilization, while the objective of bioventing is to optimize biodegradation while minimizing volatilization and capital and utility costs. Although both technologies involve venting of air though the subsurface, the different objectives result in different design and operation of the remedial systems.

The following chapters provide an overview of the principles of bioventing in relation to physical, chemical, and microbial processes occurring in the field. An overview of the development of bioventing, including development of the Bioventing Initiative, is provided as a basis for the data presented in this document. Data from Bioventing Initiative sites are used throughout this document to illustrate principles of bioventing as determined from field testing.

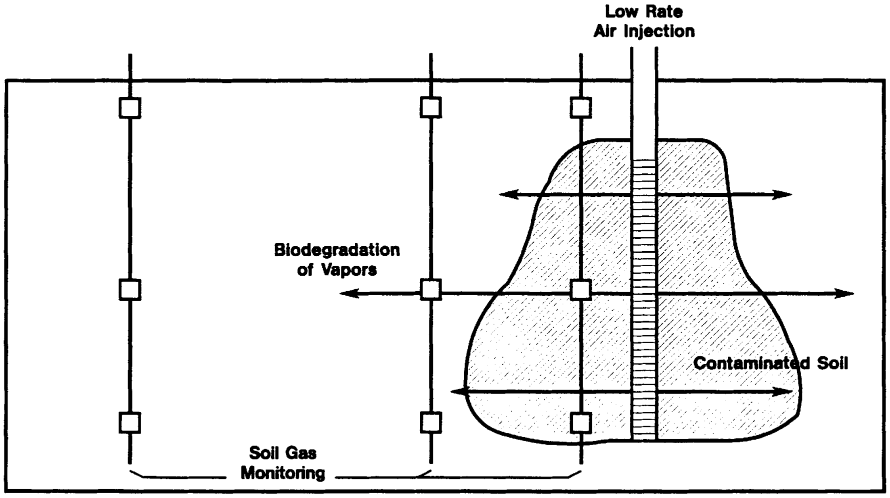


Figure 1-2. Schematic of a typical bioventing system.

Chapter 2
Development of Bioventing

This chapter provides a framework for the document, describing this development and structure of the Bioventing Initiative, and ultimately, of this document. This chapter provides an overview of bioventing, covering oxygen supply in situ (the dominant issue in the evolution of bioventing), early bioventing studies that led to development of the Bioventing Initiative, final structure of the treatability studies and bioventing system design used for the Bioventing Initiative, and finally, emerging techniques that are being investigated as modifications to the conventional bioventing design described in this document.

2.1 Oxygen Supply to Contaminated Areas

One driving force behind the development of bioventing was the difficulty of delivering oxygen in situ. Many contaminants, especially the petroleum hydrocarbons found in fuels, are biodegradable in the presence of oxygen. Traditionally, enhanced bioreclamation processes used water to carry oxygen or an alternative electron acceptor to the contaminated zone. This process was common, whether the contamination was present in the ground water or in the unsaturated zone. Media for adding oxygen to contaminated areas have included pure-oxygen-sparged water, air-sparged water, hydrogen peroxide, and air.

In all cases where water is used, the solubility of oxygen is the limiting factor. At standard conditions, a maximum of 8 mg/L to 10 mg/L of oxygen can be obtained in water when aerated, while 40 mg/L to 50 mg/L can be obtained if sparged with pure oxygen, and up to 500 mg/L of oxygen theoretically can be supplied using 1,000 mg/L of hydrogen peroxide. The stoichiometric equation shown in Equation 2-1[1] can be used to calculate the quantity of water that must be delivered to provide sufficient oxygen for biodegradation.

$$C_6H_{14} + 9.5O_2 \rightarrow 6CO_2 + 7H_2O \qquad \text{(Eq. 2-1)}$$

An example of calculating the mass of water that must be delivered for hydrocarbon degradation is shown in Example 2-1. Table 2-1 summarizes oxygen requirements based on the supplied form of oxygen.

Example 2-1. Calculation of Air-Saturated Water Mass That Must Be Delivered To Degrade Hydrocarbons: Based on Equation 2-1, the stoichiometric molar ratio of hydrocarbon to oxygen is 1:9.5. Or, to degrade 1 mole of hydrocarbons, 9.5 moles of oxygen must be consumed. On a mass basis:

$$\frac{1 \text{ mole } C_6H_{14}}{9.5 \text{ moles} O_2} \times \frac{1 \text{ mole } O_2}{32 \text{ g } O_2} \times \frac{86 \text{ g } C_6H_{14}}{1 \text{ mole } C_6H_{14}} =$$

$$\frac{86 \text{ g } C_6H_{14}}{304 \text{ g } O_2} = \frac{1 \text{ g } C_6H_{14}}{3.5 \text{ g } O_2}$$

Given an average concentration of 9 mg/L of oxygen dissolved in water, the amount of air-saturated water that must be delivered to degrade 1 g of hydrocarbon is calculated as follows:

$$\frac{3.5 \text{ g } O_2 \text{ required}}{\dfrac{9 \text{ mg } O_2}{1 \text{ L } H_2O} \times \dfrac{1 \text{ g}}{1{,}000 \text{ mg}}} = \frac{390 \text{ L } H_2O}{1 \text{ g } C_6H_{14}}$$

or, to degrade 1 lb:

$$\frac{390 \text{ L } H_2O}{1 \text{ g } C_6H_{14}} \times \frac{1 \text{ gal}}{3.8 \text{ L}} \times \frac{1{,}000 \text{ g}}{2.2 \text{ lb}} = \frac{47{,}000 \text{ gal } H_2O}{1 \text{ lb } C_6 H_{14}}$$

Table 2-1. Oxygen Requirements Based on Supplied Form

Oxygen Form	Oxygen Concentration in H_2O	Volume to Degrade 1 lb Hydrocarbon
Air-saturated H_2O	8 mg/L to 10 mg/L	47,000 gal (180,000 L)
Oxygen-saturated H_2O	40 mg/L to 50 mg/L	11,000 gal (42,000 L)
Hydrogen peroxide	Up to 500 mg/L	1,600 gal (6,100 L)
Air	NA (21% vol./vol. in air)	170 ft^3 (4,800 L)

NA = not applicable.

---

[1] See Section 3.2 for development of this equation.

Because of the low aqueous solubility of oxygen, hydrogen peroxide has been tested as an oxygen source in laboratory studies and at several field sites (Hinchee et al., 1991a; Aggarwal et al., 1991; Morgan and Watkinson, 1992). As shown in Table 2-1, if 500 mg/L of dissolved oxygen can be supplied via hydrogen peroxide, the mass of water that must be delivered decreases by more than an order of magnitude. Initially, these calculations made the use of hydrogen peroxide appear to be an attractive alternative to injecting air-saturated water.

Hydrogen peroxide is miscible in water and decomposes to release water and oxygen as shown in Equation 2-2:

$$H_2O_2 \rightarrow H_2O + \frac{1}{2}O_2 \qquad \text{(Eq. 2-2)}$$

Many substances commonly present in ground water and soil act as catalysts for the decomposition of peroxide. Important among these are aqueous species of iron and copper as well as the enzyme catalase (Schumb et al., 1955), which has significant activity in situ (Spain et al., 1989). If the rate of oxygen formation from hydrogen peroxide decomposition exceeds the rate of microbial oxygen utilization, gaseous oxygen may form because of its limited aqueous solubility. Gaseous oxygen may form bubbles, which may not be transported efficiently in ground water, resulting in ineffective oxygen delivery.

Phosphate is commonly used in nutrient formulations to decrease the rate of peroxide decomposition in groundwater applications (Britton, 1985). The effectiveness, however, of phosphate addition in stabilizing peroxide injected into an aquifer has not been well established, and different researchers have reported conflicting results (American Petroleum Institute, 1987; Brown et al., 1984; Downey et al., 1988; EPA, 1990; Morgan and Watkinson, 1992).

Hinchee et al. (1991a) conducted a field experiment to examine the effectiveness of hydrogen peroxide as an oxygen source for in situ biodegradation. The study was performed at a JP-4 jet fuel-contaminated site at Eglin AFB, Florida. Site soils consisted of fine- to coarse-grained quartz sand with ground water at a depth of 2 ft to 6 ft (0.61 m to 1.8 m). Previous studies by Downey et al. (1988) and Hinchee et al. (1989) at the same site had shown that rapid decomposition of hydrogen peroxide occurred, even with the addition of phosphate as a peroxide stabilizer. In subsequent studies, hydrogen peroxide was injected at a concentration of 300 mg/L, both with and without the addition of a phosphate-containing nutrient solution. As in previous studies, hydrogen peroxide decomposition was rapid, resulting in poor distribution of oxygen in ground water. Addition of the phosphate-containing nutrient solution did not appear to improve hydrogen peroxide stability.

Other attempts have been made to use hydrogen peroxide as an oxygen source. Although results indicate better hydrogen peroxide stability than achieved by Hinchee et al. (1989), researchers concluded that most of the hydrogen peroxide decomposed rapidly (EPA, 1990). Some degradation of aromatic hydrocarbons appears to have occurred; however, no change in total hydrocarbon contamination levels was detected in the soils (Ward, 1988).

In contrast to hydrogen peroxide use, when air is used as an oxygen source in unsaturated soil, 170 ft^3 (4,800 L) of air must be delivered to provide the minimum oxygen required to degrade 1 lb (0.45 kg) of hydrocarbon (Table 2-1). Because costs associated with water-based delivery of oxygen can be relatively high, the use of gas-phase delivery significantly reduces the cost associated with supplying oxygen.[2]

An additional advantage of using a gas-phase process is that gases have greater diffusivity than liquids. At many sites, geological heterogeneities cause fluid that is pumped through the formation to be channeled into more permeable pathways (e.g., in an alluvial soil with interbedded sand and clay, all fluid flow initially takes place in the sand). As a result, oxygen must be delivered to the less permeable clay lenses through diffusion. In a gaseous system (as found in unsaturated soils), this diffusion can be expected to take place at rates at least three orders of magnitude greater than rates in a liquid system (as is found in saturated soils). Although diffusion cannot realistically be expected to aid significantly in water-based bioreclamation, diffusion of oxygen in a gas-phase system is a significant mechanism for oxygen delivery to less permeable zones.

Given the advantages of using air rather than water as the oxygen source, several investigators began exploring the feasibility of an air-based oxygen supply system as a remedial option. A summary of the results of these investigations is presented in the following section.

2.2 Bioventing Research and Development

Figure 2-1 provides a historical perspective of bioventing research and development. To the authors' knowledge, the first documented evidence of unsaturated-zone biodegradation resulting from forced aeration was reported by the Texas Research Institute, Inc., in a 1980 study for the American Petroleum Institute. A large-scale model experiment was conducted to test the effectiveness of a surfactant treatment to enhance the recovery of spilled gasoline. The experiment accounted for only 8 gal (30 L) of the 65 gal (250 L) originally spilled and raised questions about the fate of the gasoline.

---

[2] See Chapter 5 of Volume II for a comparison of costs associated with hydrogen peroxide use versus air (bioventing).

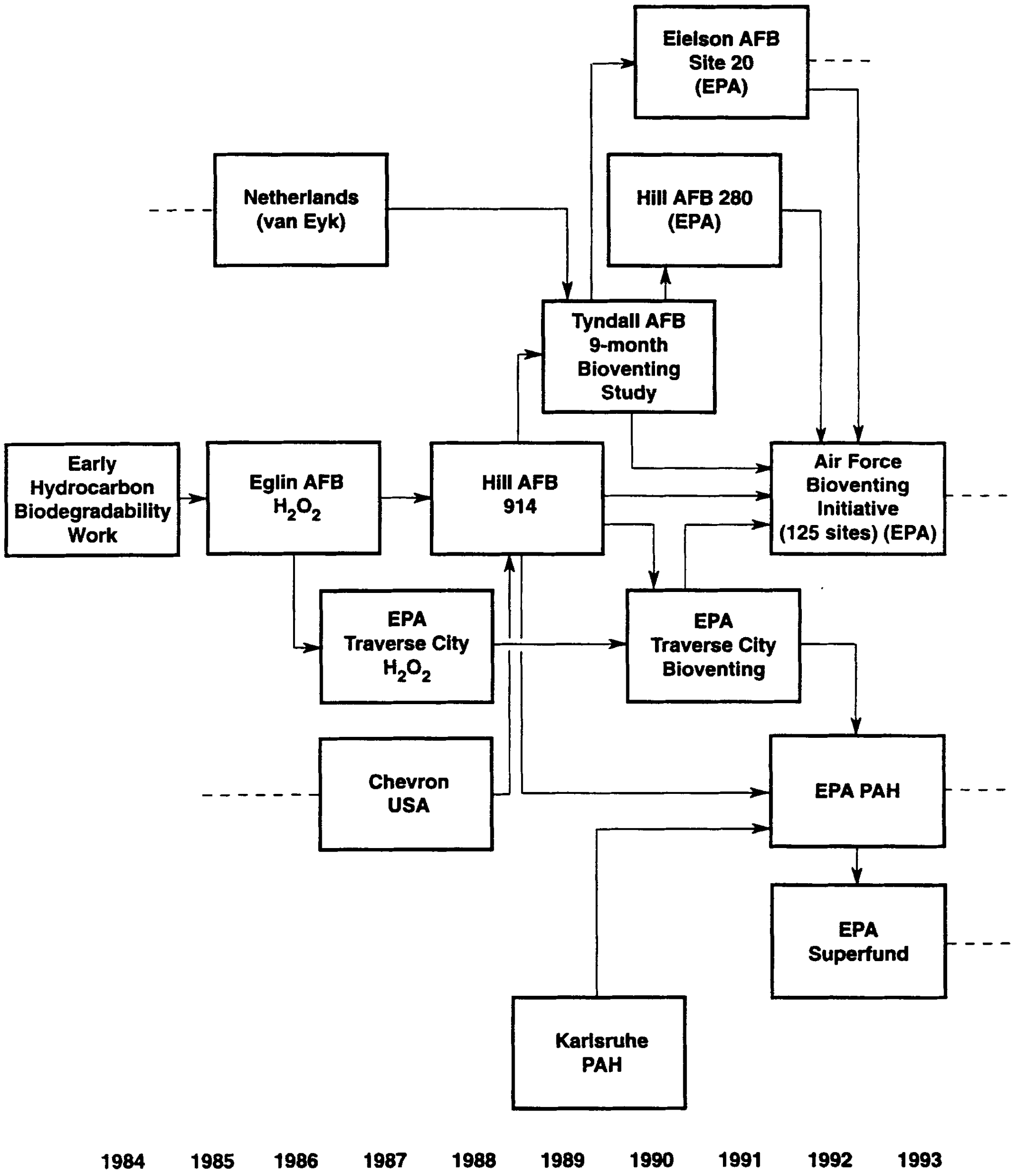


Figure 2-1. Historical perspective on the development of bioventing.

Subsequently, a column study was conducted to determine a diffusion coefficient for soil venting. This column study evolved into a biodegradation study in which researchers concluded that as much as 38 percent of the fuel hydrocarbons were biologically mineralized. Researchers also concluded that venting not only would remove gasoline by physical means but also would enhance microbial activity and promote biodegradation of the gasoline (Texas Research Institute, 1980, 1984).

To the authors' knowledge, the first actual field-scale bioventing experiments were conducted by Jack van Eyk for Shell Research. In 1982, at van Eyk's direction, the Shell Laboratory in Amsterdam, The Netherlands, initiated a series of experiments to investigate the effectiveness of bioventing for treating hydrocarbon-contaminated soils. These studies were reported in a series of papers (Anonymous, 1986; Staatsuitgeverij, 1986; van Eyk and Vreeken, 1988, 1989a, and 1989b).

Wilson and Ward (1986) suggested that using air as a carrier for oxygen could be 1,000 times more efficient than using water, especially in deep, hard-to-flood unsaturated zones. They made the connection between oxygen supply via soil venting and biodegradation by observing that "soil venting uses the same principle to remove volatile components of the hydrocarbon." In a general overview of the soil venting process, Bennedsen et al. (1987) concluded that soil venting provides large quantities of oxygen to the unsaturated zone, possibly stimulating aerobic degradation. They suggested that water and nutrients also would be required for significant degradation and encouraged additional investigation into this area.

Biodegradation enhanced by soil venting has been observed at several field sites. Investigators claim that at a soil venting site for remediation of gasoline-contaminated soil, significant biodegradation occurred (measured by a temperature rise) when air was supplied. Investigators pumped pulses of air through a pile of excavated soil and observed a consistent rise in temperature, which they attributed to biodegradation. They claimed that the pile was cleaned up during the summer primarily by biodegradation (Conner, 1989). They did not, however, control for natural volatilization from the aboveground pile, and insufficient data were published to critically review their biodegradation claim.

Researchers at Traverse City, Michigan, observed a decrease in the toluene concentration in unsaturated zone soil gas, which they measured as an indicator of fuel contamination in the unsaturated zone. They assumed that advection had not occurred and attributed the toluene loss to biodegradation. The investigators concluded that because toluene concentrations decayed near the oxygenated ground surface, soil venting is an attractive remediation alternative for biodegrading light volatile hydrocarbon spills (Ostendorf and Kampbell, 1989).

The U.S. Air Force initiated its research and development program in bioventing in 1988 with a study at Site 914,[3] Hill AFB, Utah. This site was initially operated as a soil vapor extraction unit but was modified to a bioventing system after 9 months of operation because of evidence that biodegradation was occurring and also as part of an attempt to decrease costs by reducing off-gas. Moisture and nutrient addition were studied at this site; however, although moisture addition appeared to improve biodegradation, nutrient addition did not. Final soil sampling demonstrated that benzene, toluene, ethylbenzene, and xylenes (BTEX) and total petroleum hydrocarbon (TPH) levels decreased to below regulatory levels, and this site became the first Air Force site that was closed through in situ bioremediation. This study revealed that bioventing had great potential for remediating JP-4 jet fuel-contaminated soils. The study also showed, however, that additional research would be needed before the technology could be routinely applied in the field.

Following the Site 914, Hill AFB study, a more controlled bioventing study was completed at Tyndall AFB,[4] Florida. This study was designed to monitor specific process variables and the subsequent effect on biodegradation of hydrocarbons. Several important findings resulted from this study, including the effect of air flow rates on removal by biodegradation and volatilization, the effect of temperature on biodegradation rates, the lack of microbial stimulation from the addition of moisture and nutrients, and the importance of natural nitrogen supply through nitrogen fixation. In addition, initial and final contaminant measurements showed over 90 percent removal of BTEX. This study was short-term but illustrated the effectiveness of bioventing.

The studies conducted at Hill and Tyndall AFBs provided valuable information on bioventing. These studies also showed, however, that long-term, controlled bioventing studies were necessary to fully evaluate and optimize the technology. In 1991, long-term bioventing studies were initiated at Site 280, Hill AFB, Utah, and Site 20, Eielson AFB, Alaska.[5] These studies were joint efforts between EPA and the U.S. Air Force Environics Directorate of the Armstrong Laboratory. These studies have involved intensive monitoring of several process variables, including the effect of soil temperature on biodegradation rates, surface emission analyses, and optimization of flow rate.

Based on the success of these previous studies, in 1992, AFCEE initiated the Bioventing Initiative, where pilot-scale bioventing systems were installed at 125 contaminated sites located throughout the continental United States and in Hawaii, Alaska, and Johnston Atoll (Figure 2-2). Sites varied dramatically in climatic and geologic conditions. Contaminants typically were petroleum hydrocarbons from JP-4 jet fuel, heating oils, waste oils, gasoline, and/or diesel; however, some fire training areas also were studied where significant concentrations of solvents were present. This manual represents the culmination of this study and is the product of the data collected from these sites and other projects.

In addition to these studies, other bioventing studies have been conducted by several researchers. A summary of data from some sites where bioventing has been applied is shown in Table 2-2.[6] The scale of application and contaminant type is given, as well as the biodegradation rate, if known. The studies listed in Table 2-2 are limited to those where the study was conducted in situ, where no inoculum was added to site soils, and where flow rates were optimized for biodegradation, not volatilization. A distinction must be made between bioventing and SVE systems. Bioventing systems operate at flow rates optimized for biodegradation, not volatilization, although some volatilization may occur. SVE systems operate at flow rates optimized for volatilization, although some biodegradation may occur. Therefore, flow rates and configurations of the two systems are significantly different.

---

[3] See Section 4.1 for a detailed discussion of this study.

[4] See Section 4.2 for a detailed discussion of this study.

[5] See Sections 4.3 and 4.4, respectively, for a detailed discussion of these studies.

[6] Only select Bioventing Initiative sites are included in this table. A presentation of data from all Bioventing Initiative sites is provided in Section 4.1.

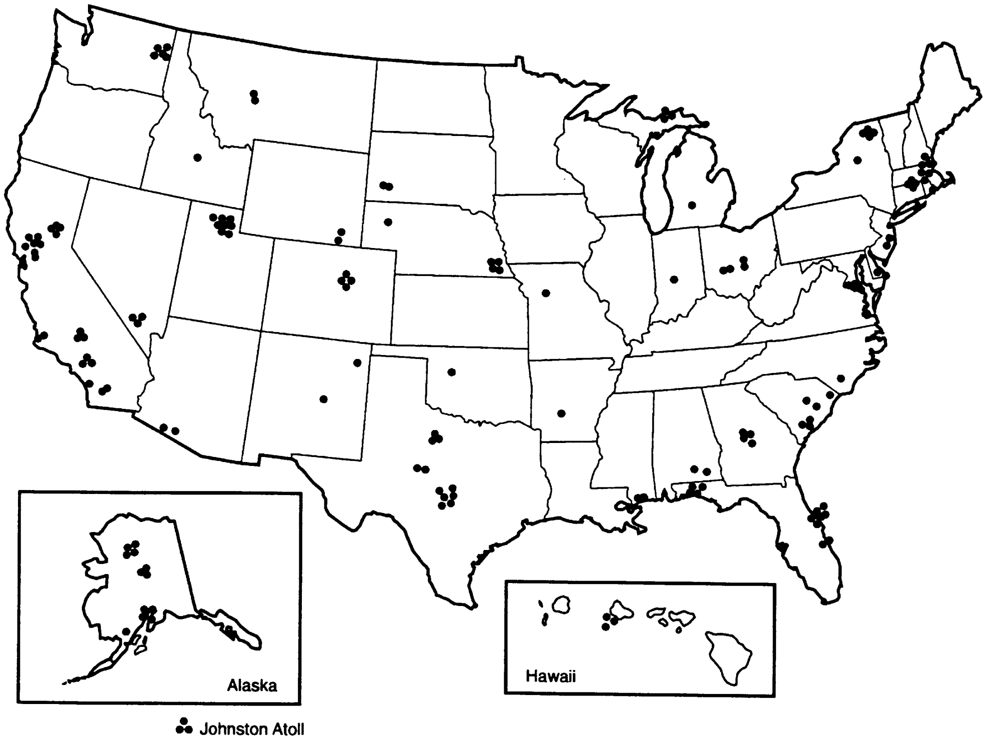


Figure 2-2. Locations of Bioventing Initiative sites.

The following section describes the basic structure for field studies conducted as part of the Bioventing Initiative. Data from these studies were used to generate this document.

2.3 Structure of Bioventing Initiative Field Treatability Studies and Bioventing System Design

The design of the field treatability studies and final bioventing system was developed based on experience from previous studies at Hill, Tyndall, and Eielson AFBs. The *Test Plan and Technical Protocol for a Treatability Test for Bioventing* (Hinchee et al., 1992) was written to standardize all field methods, from treatability tests to well installations. This allowed for collection of consistent data from 125 sites, which provided a strong database for evaluating bioventing potential. At all sites, the following activities were conducted:

- Site characterization, including a small-scale soil gas survey and collection of initial soil and soil gas samples for analysis of BTEX, TPH, and soil physicochemical characteristics.
- Field treatability studies, including an in situ respiration test and a soil gas permeability test.
- Identification of a background, uncontaminated area for comparison with the contaminated area of background respiration rates and nutrient levels.
- Installation of a blower for 1 year of operation (typically configured for air injection), if results of field treatability studies were positive.
- Conduct of 6-month and 1-year in situ respiration tests at sites where a blower was installed.
- Collection of final soil and soil gas samples for analyses of BTEX and TPH.

Of particular significance were the use of the in situ respiration test to measure microbial activity and the use of air injection instead of extraction for air delivery.

The in situ respiration test was developed to rapidly measure aerobic biodegradation rates in situ at discrete locations.[7] Biodegradation rates calculated from the in situ respiration test are useful for (1) assessing the potential application of bioremediation at a given site, (2) estimating the time required for remediation at a given site, and (3) providing a measurement tool for evaluating the effects of environmental parameters on microbial activity and ultimately on bioventing performance. The actual effect of individual parameters on microbial activity is difficult to assess in the field because of interference and interactions among these parameters. The in situ respiration test integrates all factors to assess whether the microorganisms are metabolizing the fuel.

---

[7] See Section 1.4 of Volume II for methods for conducting the in situ respiration test and analyses of test data.

Table 2-2. Summary of Reported in Situ Respiration Rates and Bioventing Data

Site	Scale of Application	Contaminant	In Situ Respiration Rates (mg/kg-day Unless Marked)	Reference
Albemarle County, VA	Pilot scale	Acetone, toluene, benzene, naphthalene	1.5-26	Leeson et al., 1994
Eielson AFB, AK	Pilot scale	JP-4 jet fuel	0.82-8.2	Hinchee and Ong, 1992 Leeson et al., 1995 EPA, 1994c
Fallon NAS, NE	In situ respiration test	JP-5 jet fuel	4.2	Hinchee et al., 1991b
Galena AFS, AK, Saddle Tank Farm	Pilot scale	Diesel	11-30	Ong et al., 1994
Hill AFB, Utah, Site 914	Full scale, 2 years	JP-4 jet fuel	Up to 8.5	Hinchee et al., 1994
Hill AFB, Utah, Site 280	Full scale	JP-4 jet fuel	0.27 (site average)	Battelle, 1994 EPA, 1991b
Eglin AFB, FL	Full scale	Gasoline	4.0	Downey et al., 1994
Kenai, Alaska, Site 1-33	Pilot scale	Crude oil, petroleum	2.7-25	Hinchee, unpublished data
Kenai, Alaska, Site 3-9	Pilot scale	Crude oil	0.64-12	Hinchee, unpublished data
Massachusetts	Full scale	Gasoline	Not measured	Brown and Crosbie, 1994
Minnesota	Full scale	Gasoline	15, 4.9, 3.1, 0.20	Newman et al., 1993
The Netherlands	Full scale	Gasoline	570 kg of hydrocarbon removed during 2-year study	van Eyk, 1994
The Netherlands	Undefined	Undefined	1.6-4.2	Urlings et al., 1990
The Netherlands	Field pilot, 1 year	Diesel	6.9	van Eyk and Vreeken, 1989b
Patuxent River NAS, MD	In situ respiration test	JP-5 jet fuel	2.6	Hinchee et al., 1991b
Prudhoe Bay	Pilot scale	Diesel	8.6-11	Ong et al., 1994
St. Louis Park, MN, Reilly Tar Site	Pilot scale	PAH	0.55-2.2 mg PAH/kg-day	Alleman et al., 1995
Seattle, WA	Full scale	Diesel	6.0	Baker et al., 1993
Southern CA	Full scale	Gasoline, hydraulic oil	0.14	Zachary and Everett, 1993
Tinker AFB, OK	In situ respiration test	JP-4 and mixed fuels	2.3-15	Hinchee and Smith, 1991
Tyndall AFB, FL	Field pilot, 1-year and in situ respiration test	JP-4 jet fuel	1.6-16	Miller, 1990 Hinchee et al., 1991b
Undefined	Full scale	Gasoline and diesel	50 kg/(well day)	Ely and Heffner
Undefined	Full scale	Diesel	100 kg/(well day)	Ely and Heffner, 1988
Undefined	Full scale	Fuel oil	60 kg/(well day)	Ely and Heffner, 1988
Valdez, Site A	Pilot scale	Crude oil	0.90-15.6	Hinchee, unpublished data

Data from the in situ respiration test and site measurements were used to conduct a statistical analysis of the observed effects of the site measurements on microbial activity in the field. The statistical analysis was constructed to account for parameter interactions. These results are discussed in detail in Chapter 5.

Also of note is that 120 of the 125 bioventing systems installed were configured for air injection. Before the bioventing studies conducted at Hill (Site 280) and Eielson AFBs, bioventing systems were typically operated in the extraction configuration, similar to SVE systems. Research at Hill and Eielson AFB's, however, demonstrated that air injection was a feasible, more efficient alternative to air extraction, resulting in a greater proportion of hydrocarbon biodegradation rather than volatilization and reduced air emissions.[8] Therefore, the

---

[8] See Section 2.1 of Volume II for a discussion of air injection versus extraction considerations.

air injection configuration was selected for the basic bioventing system at Bioventing Initiative sites.

The results generated from the Bioventing Initiative are summarized in detail in Chapter 5 but also are used to illustrate basic principles of bioventing and microbial processes discussed in Chapter 3. The design guidelines presented in this manual are the result primarily of the information gained from installing and operating the 125 Bioventing Initiative sites. These design guidelines represent the basic bioventing system, which is applicable to the majority of sites suitable for bioventing. The following section addresses emerging techniques for modifying the basic bioventing system for use at sites that are not amenable to standard bioventing methods.

2.4 Emerging Techniques for Modifications to Bioventing Systems

Several techniques are being investigated as a means of modifying the conventional bioventing system described in this document. These techniques have not been tested extensively in the field; therefore, their potential feasibility is unknown. These techniques are briefly presented in this section to illustrate their potential application.

The bioventing modifications being investigated are designed to address specific challenges in bioventing including:

- *Injection of pure oxygen instead of air for treatment of low-permeability soils:* Because only low flow rates are possible in low-permeability soil, injection of pure oxygen may be useful for providing larger oxygen concentrations for a given volume than is possible with air injection.
- *Soil warming for bioventing in cold climates:* Soil warming can be used to increase biodegradation rates, thus decreasing remediation times. This technique has been studied in detail at Site 20, Eielson AFB, Alaska[9] but would only be an option in extreme environments.
- *Remediation of recalcitrant compounds through ozonation:* Ozonation may be used to partially oxidize more recalcitrant contaminants, making them more susceptible to biodegradation. This technique would not be necessary at petroleum-contaminated sites but may be considered at sites contaminated with compounds such as polycyclic aromatic hydrocarbons (PAHs) or pesticides.
- *Remediation of contaminated saturated soils through air sparging:* Air sparging is being investigated as a means of aerating saturated soil to enhance biodegradation and volatilization. Studies to date, however, have been inconclusive concerning its effectiveness because the studies lacked adequate controls and measurement techniques.

The techniques described above represent potential future areas of investigation in the bioremediation field. The following chapters describe the principles of bioventing, which also apply to the techniques described in this section.

---

[9] See Section 4.4 for a discussion of this site and the cost benefits of soil warming.

Chapter 3
Principles of Bioventing

In this chapter, basic principles fundamental to the bioventing process are discussed to provide a clear understanding of the many physical, chemical, and biological processes that affect the ultimate feasibility of bioventing. Recognizing the significance of these different processes will lead to more efficient bioventing design and operation. Specific topics addressed in this chapter include:

- Soil gas permeability, contaminant diffusion and distribution, and zone of oxygen influence.
- Environmental factors that affect microbial processes, such as electron acceptor conditions, moisture content, pH, temperature, nutrient supply, contaminant concentration, and bioavailability.
- Subsurface distribution of an immiscible liquid.
- Compounds targeted for removal through bioventing.
- BTEX versus TPH removal during petroleum bioventing.

3.1 Physical Processes Affecting Bioventing

Three primary physical characteristics affect bioventing. These include soil gas permeability, contaminant diffusion and distribution, and zone of oxygen influence. Each of these parameters is discussed in the following sections.

3.1.1 Soil Gas Permeability

Assuming contaminants are present that are amenable to bioventing, geology probably is the most important site characteristic for a successful bioventing application. Soils must be sufficiently permeable to allow movement of enough soil gas to provide adequate oxygen for biodegradation, approximately 0.25 to 0.5 pore volumes per day.

Soil gas permeability is a function of soil structure and particle size, as well as moisture content. Typically, permeability in excess of 0.1 darcy is adequate for sufficient air exchange. Below this level, bioventing certainly is possible, but field testing may be required to establish feasibility. When the soil gas permeability falls below approximately 0.01 darcy, soil gas flow is primarily through either secondary porosity (e.g., fractures) or any more permeable strata that may be present (e.g., thin sand lenses). Therefore, the feasibility of bioventing in low-permeability soils is a function of the distribution of flow paths and diffusion of air to and from the flow paths within the contaminated area.

In a soil that is of reasonable permeability, a minimum separation of 2 ft to 4 ft (0.61 m to 1.2 m) between vertical and horizontal flow paths and contaminant may still result in successful treatment because of oxygen diffusion. The degree of treatment, however, will be very site-specific.

Bioventing has been successful in some low-permeability soils, such as a silty clay site at Fallon Naval Air Station (NAS), Nevada (Kittel et al., 1995), a clayey site at Beale AFB, California (Phelps et al., 1995), a silty site at Eielson AFB, Alaska (Leeson et al., 1995), a silty clay site in Albemarle County, Virginia (Leeson et al., 1994), and many Bioventing Initiative sites. Grain size analysis was conducted on several samples from each site in the Bioventing Initiative. The relative distribution of fine-grained soils is illustrated in Figure 3-1. Sufficient soil gas permeability has been demonstrated at many sites with silt and clay contents exceeding 80 percent by weight. Approximately 50 percent of the sites tested

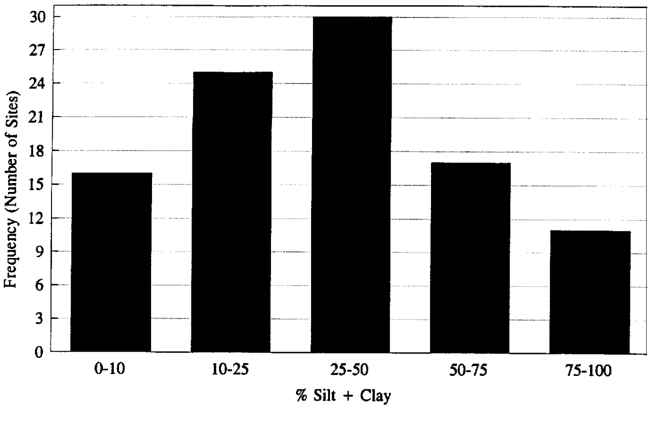


Figure 3-1. Distribution of fine-grained soils (silt and clay) at Bioventing Initiative sites.

contained greater than 50 percent clay and silt fractions. Oxygen distribution has generally been adequate in soils where permeability values exceeded 0.1 darcy, with oxygen detected at ambient levels in all nine of the monitoring points installed. Few sites had permeability less than 0.1 darcy; therefore, data are limited for analysis. The greatest limitation to bioventing at Bioventing Initiative sites has been excessive soil moisture. A combination of high soil moisture content and fine-grained soils has made bioventing impractical at only three of the 125 test sites, however.

In general, our calculated soil gas permeability values have exceeded suggested values reported in Johnson et al. (1990) for silt and clay soils. This is probably because of the heterogeneous nature of most soils, which contain lenses of more permeable material or fractures that aid in air distribution.

3.1.2 Contaminant Distribution

Another important factor affecting the feasibility of bioventing is contaminant distribution throughout the site. Because bioventing is in essence an air delivery system designed to efficiently provide sufficient oxygen to contaminated soils, a clear understanding of subsurface contaminant distribution is a necessity. Many sites at which bioventing can be applied are contaminated with immiscible liquids, such as petroleum hydrocarbons. When a fuel release occurs, the contaminants may be present in any or all of four phases in the geologic media:

- Sorbed to the soils in the vadose zone.
- In the vapor phase in the vadose zone.
- In free-phase form floating on the water table or as residual saturation in the vadose zone.
- In the aqueous phase dissolved in pore water in the vadose zone or dissolved in the ground water.

Of the four phases, dissolved petroleum contaminants in ground water frequently are considered to be of greatest concern due to the risk of humans being exposed to contaminants through drinking water. The free-phase and sorbed-phase hydrocarbons, however, act as feed stocks for ground-water contamination, so any remedial technology aimed at reducing ground-water contamination must address these sources of contamination. Also, hydrocarbons in the vadose zone can produce a volatile organic carbon (VOC) threat in subsurface buildings or structures.

Immiscible liquids are classified as less dense nonaqueous phase liquids (LNAPLs) if their density is less than water or dense nonaqueous phase liquids (DNAPLs) if their density is greater than water. In general, most petroleum hydrocarbons, such as gasoline, are LNAPLs, whereas most chlorinated solvents, such as trichloroethylene (TCE), are DNAPLs. Because of these differences in densities, subsurface spills of LNAPLs and DNAPLs behave differently at a given site, with LNAPLs distributed primarily in the vadose zone and DNAPLs distributed in both the unsaturated and saturated zones. Because bioventing is primarily a vadose zone treatment process, this discussion focuses on the behavior of LNAPLs.

When a large-enough fuel spill occurs, the fuel is retained within approximately 10 percent to 20 percent of the pore volume of the soil and may eventually come to rest on the water table. Contaminants then partition among the various phases existing within the subsurface environment. Fluids can move through the subsurface via various mechanisms, such as advection and diffusion. LNAPLs are likely to migrate through the vadose zone relatively uniformly until they reach the capillary fringe. The LNAPLs will then spread laterally along the saturated zone. Water table fluctuation may result in LNAPL below the water table; however, an LNAPL will not permeate the water-saturated zone unless a critical capillary pressure is exceeded, which is a function of the porous medius pore sizes.

In the vadose zone, components of the LNAPL may partition into the vapor phase or the aqueous phase (pore water), sorb onto solids, or remain in the free product. Contaminants in free product may partition into the vapor phase, depending on their vapor pressures at the temperature and pressure existing in the vadose zone. Once in the vapor phase, these contaminants can migrate in response to advection and diffusion. Raoult's Law is used to describe partitioning at equilibrium between an immiscible and a vapor phase:

$$C_v = \chi\, C_{vsat} \qquad \text{(Eq. 3-1)}$$

where:

C_V = volumetric concentration of the contaminant (x) in the vapor phase (g_x/L_{vapor})

χ = mole fraction of the contaminant (dimensionless)

C_{vsat} = saturated vapor concentration of the contaminant (g_x/L_{vapor})

C_{vsat} is further defined as:

$$C_{vsat} = \frac{(MW_x)\, P_v}{RT_{abs}} \qquad \text{(Eq. 3-2)}$$

where:

MW_x = molecular weight of the contaminant ($gx/mole_x$)

P_V = vapor pressure of pure contaminant at temperature T (atm)

R = gas constant (L-atm/mole-°K); and

T_{abs} = absolute temperature (°K)

Free product in contact with ground water may leach contaminants into the ground water, or contaminants may dissolve into pore water in the vadose zone, depending on the solubility of specific components. Once in the ground water, contaminants can migrate through the subsurface in response to a gradient in the aqueous-phase total potential (i.e., advection) or by a difference in the aqueous-phase chemical concentrations. The equilibrium relationship between the aqueous and the immiscible phases is described as:

$$C_w = \chi\, s_x \qquad \text{(Eq. 3-3)}$$

where:

C_V = volumetric concentration of the contaminant x in the aqueous phase ($g_x/L_{aqueous}$)

χ = mole fraction of the contaminant (dimensionless)

s_x = solubility of pure contaminant x in water (g_x/L_{water})

Sorption of contaminants is a complex process involving several different phenomena, including coulomb forces, London-van der Waals forces, hydrogen bonding, ligand exchange, dipole-dipole forces, dipole-induced dipole forces, and hydrophobic forces. In the case of hydrocarbons, because of their nonpolar nature, sorption most often occurs through hydrophobic bonding to organic matter. Hydrophobic bonding often is a dominant factor influencing the fate of organic chemicals in the subsurface (DeVinny et al., 1990). The degree of sorption generally is empirically related by the organic content of the soil and the octanol-water partition coefficient of a particular compound.

Sorption isotherms generally follow one of three shapes: Langmuir, Freundlich, or linear (Figure 3-2). The Langmuir isotherm describes the sorbed contaminant concentration as increasing linearly with concentration, then leveling off as the number of sites available for sorption are filled. This isotherm accurately describes the situation at or near the contaminant source, where concentrations are high. The Freundlich isotherm assumes an infinite number of sorption sites, which would accurately describe an area some distance from the contaminant source, where concentrations are dilute. The mathematical expression contains a chemical-specific coefficient that may alter the linearity of the isotherm. The linear isotherm is relatively simple and is valid for dissolved compounds at less than one-half of their solubility (Lyman et al., 1992). This isotherm is typically valid to describe hydrocarbon sorption.

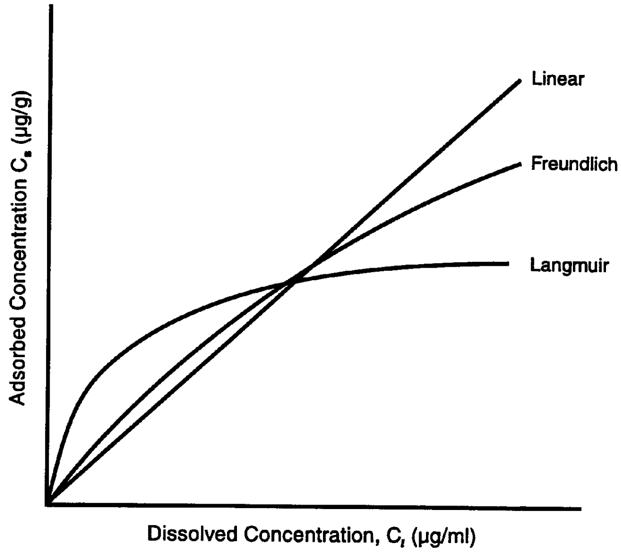


Figure 3-2. Sorption isotherms.

The linear isotherm is expressed mathematically as:

$$C_s = K_d\, C_w \qquad \text{(Eq. 3-4)}$$

where:

C_S = quantity of contaminant x sorbed to the solid matrix (g_x/g_{soil})

K_d = sorption coefficient ($L_{aqueous}/g_{soil}$)

C_W = volumetric concentration of contaminant x in the aqueous phase ($g_x/L_{aqueous}$)

The sorption coefficient may be determined experimentally, estimated based on values published in the literature or estimated using the octanol/water partition coefficient (K_{ow}) and the organic carbon fraction (f_{oc}) of the soil. The sorption coefficient can be estimated using the following mathematical expression:

$$K_d = K_{ow}\, f_{oc} \qquad \text{(Eq. 3-5)}$$

Some values for K_{ow} are provided in Table 3-1.

In practice, at equilibrium, the concentration of most petroleum hydrocarbon compounds of interest in the aqueous or vapor phases is driven by the immiscible phase, if present, and the sorbed phase, if the immiscible phase is not present. If no immiscible phase is present, and all sorption sites on the solid soil matrix are

Table 3-1. Values for Key Properties of Select Petroleum Hydrocarbons

Compound	K_{ow}	Solubility (mg/L)	Vapor Pressure (mm Hg)[a]
Benzene	131.82	1,750[b]	75
Ethylbenzene	1,349	152[b]	$10^{79^\circ F}$
Heptane	—	50	40
Hexane	—	20	150
Toluene	489.9	537[c]	$20^{65^\circ F}$
o-xylene	891	152[b]	7
m-xylene	1,585	158[b]	9
p-xylene	1,513.6	198[b]	9

[a] Vapor pressure at 68°F unless noted.
[b] Calculated at 20°C.
[c] Calculated at 20°C.

not occupied,[1] the vapor- or aqueous-phase concentration is a function of the sorbed concentration. This relationship is illustrated in Figure 3-3.

This relationship typically follows a Langmuir type curve. If the concentration in the soil is in excess of the sorption capacity of the soil,[2] the aqueous-phase and the vapor-phase concentrations are Raoult's Law-driven and are independent of the hydrocarbon concentration in the soil. This is an important concept in attempting to interpret soil gas or ground-water data. For example, in a sandy site at which free product has been detected, the highest soil hydrocarbon concentrations may exceed 25,000 mg/kg. Yet, 99 percent remediation to 250 mg/kg may not affect the equilibrium soil gas or ground-water hydrocarbon concentrations.

In terms of contaminant distribution, difficulties in applying bioventing arise when significant quantities of the contaminant are in the capillary fringe or below the water table because of ground-water fluctuations. Treatment of the capillary fringe is possible, and screening of venting wells below the water table is recommended to ensure treatment of this area.[3] The ability of bioventing to aerate the capillary fringe and underlying water table has not been evaluated, however. Limited oxygenation is anticipated because of water-filled pore space. If significant contamination exists below the water table, dewatering should be considered as a means of exposing any contaminated soil to injected air. Alternatively, a combination of air sparging and bioventing may provide more efficient air delivery to the capillary fringe; however, air sparging has not been well documented, and many parameters are still unknown concerning its applicability and effectiveness.

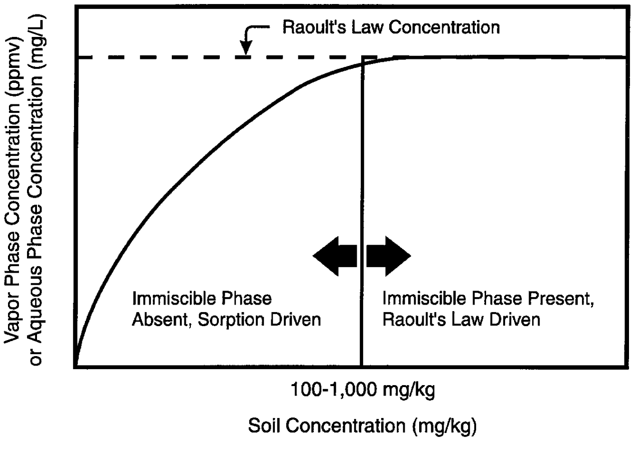


Figure 3-3. Relationship between sorbed contaminant concentrations and vapor- or aqueous-phase concentrations.

3.1.3 Oxygen Radius of Influence

An estimate of the oxygen radius of influence (R_I) of venting wells is an important element of a full-scale bioventing design. This measurement is used to design full-scale systems, specifically to space venting wells, to size blower equipment, and to ensure that the entire site receives a supply of oxygen-rich air to sustain in situ biodegradation.

The radius of oxygen influence is defined as the radius to which oxygen has to be supplied to sustain maximal biodegradation. This definition of radius of influence is different than is typically used for SVE, where radius of influence is defined as the maximum distance from the air extraction or injection well where vacuum or pressure (soil gas movement) occurs. The oxygen radius of influence is a function of both air flow rates and oxygen utilization rates, and therefore depends on site geology, well design, and microbial activity.

The radius of influence is a function of soil properties but also is dependent on the configuration of the venting well, extraction or injection flow rates, and microbial activity, and also is altered by soil stratification. In soils with less permeable lenses adjacent to more permeable soils, injection into the permeable layer produces a greater radius of influence than could be achieved in homogeneous soils. On sites with shallow contamination, the radius of influence also may be increased by impermeable surface barriers such as asphalt or concrete. Frequently, however, paved surfaces do not act as vapor barriers. Without a tight seal to the native soil surface,[4] the pavement does not significantly affect soil gas flow.

Microbial activity affects the oxygen radius of influence. As microbial activity increases, the effective treated area decreases. Therefore, a desirable approach is to estimate the oxygen radius of influence at times of peak microbial activity and to design the bioventing system based on these measurements.

3.2 Microbial Processes Affecting Bioventing

Biological treatment approaches rely on organisms to destroy or reduce the toxicity of contaminants. The advantages of chemical and physical treatment approaches generally are outweighed by the ability of microorganisms to mineralize contaminants, thereby eliminating the process of transferring contaminants from one medium (i.e., soil and soil vapor) into another medium (i.e., activated carbon) that will still require treatment. In addition, microbial processes allow treatment of

---

[1] In most soils, this is probably at a concentration of less than 100 mg/kg to 1,000 mg/kg.

[2] In most soils, this is probably at a concentration of less than 100 mg/kg to 1,000 mg/kg

[3] See Section 2.5 of Volume II for a discussion of vent well construction.

[4] Based on the author's experience, this seal does not occur at most sites.

large areas relatively inexpensively and with relatively noninvasive techniques. This section discusses kinetics of microbial metabolism and environmental parameters that affect the microbial processes bioventing is dependent upon, thereby potentially affecting the efficacy of bioventing.

3.2.1 Microbial Kinetics

In biological processes, microorganisms degrade organic compounds either directly to obtain carbon and/or energy, or fortuitously in a cometabolic process with no significant benefit to the microorganism. As an example, a stoichiometric equation describing degradation of *n*-hexane is shown:

$$\begin{aligned} & C_6H_{14} + 7.875O_2 + 0.25NO_3 \rightarrow \\ & CH_2O_{0.5}N_{0.25}(\text{biomass}) + \\ & 5CO_2 + 6H_2O \qquad \text{(Eq. 3-6)} \end{aligned}$$

In the case of bioventing, where microorganisms are stimulated in situ, the microorganisms are at equilibrium, and little net biomass growth occurs. In other words, biomass decay approximately balances biomass growth. Consequently, where no net biomass is produced, Equation 3-6 reduces to:

$$C_6H_{14} + 9.5O_2 \rightarrow 6CO_2 + 7H_2O \qquad \text{(Eq. 3-7)}$$

Based on Equation 3-7, 9.5 moles of oxygen are required for every mole of hydrocarbon consumed, or, on a weight basis, approximately 3.5 g of oxygen are required for every 1 g of hydrocarbon consumed.

Predicting the amount of time needed to bioremediate a site requires an understanding of the microbial kinetics of substrate (contaminant) utilization. Most substrate utilization falls under the heading of primary substrate utilization, in which growth on a carbon source supplies most of the carbon and energy for the microorganism. In cases where a contaminant does not supply the primary source or cannot be used for carbon and energy, secondary substrate utilization or cometabolism may occur. During the bioventing process, primary substrate utilization generally describes the kinetics of the reactions taking place; however, in some instances, cometabolic processes also may occur. For example, at sites contaminated with both fuels and solvents, such as TCE, cometabolic bioventing may account for degradation of TCE.

Primary substrate utilization has been described through an empirical approach by the Monod expression:

$$-\frac{dS}{dt} = \frac{kXS}{K_s + S} \qquad \text{(Eq. 3-8)}$$

where:

S = concentration of the primary substrate (contaminant) (g_S/L)

t = time (minutes)

k = maximum rate of substrate utilization (g_S/g_X-min)

X = concentration of microorganisms (g_X/L)

K_S = Monod half-velocity constant (g_S/L)

At high substrate concentrations (S is greater than K_S), the rate of substrate utilization is at a maximum, limited by some other factor such as oxygen, nutrients, or the characteristics of the microorganism. In this instance, the rate of substrate utilization is first-order with respect to cell density but zero-order with respect to substrate concentration. Conversely, when the primary substrate concentration is very low (S is less than K_S), the substrate utilization rate is first-order with respect to both cell density and substrate concentration. In a well-designed bioventing system, kinetics based on oxygen utilization are zero-order. The rate based on petroleum or other contaminant removal may be described, however, by Monod or inhibition kinetics.

Monod kinetics have been widely applied to conventional wastewater treatment, where the compounds being treated generally are bioavailable and readily degradable. Bioventing typically is applied to aerobically biodegradable compounds; however, the maximum rate of biodegradation (k) is much lower than for most wastes in conventional wastewater treatment. For example, Howard et al. (1991) estimated that benzene has an aerobic half-life (dissolved in ground water) of 10 days to 24 months, whereas ethanol (a compound more typical of conventional wastewater treatment) is estimated to have a half-life of 0.5 to 2.2 days. Bioventing kinetics are further complicated by bioavailability of the contaminants, driven at least in part by solubilization. Because microorganisms exist in pore water, contaminants must partition into the pore water to be available for degradation. Although high soil contaminant concentrations may be present, the actual concentration of hydrocarbon dissolved in the pore water and available to the microorganisms may be low.

In practice, oxygen utilization rates tend to decline slowly with time during remediation. At many sites, this trend may be difficult to follow over periods of less than 1 to 3 years because of other variables affecting the rate, such as temperature and soil moisture. This decline may not be indicative of true first-order kinetics but may simply be the result of selective early removal of more degradable compounds, such as benzene.

3.2.2 Environmental Parameters Affecting Microbial Processes

Bioventing depends upon providing microorganisms optimal conditions for active growth. Several factors may affect a microorganism's ability to degrade contaminants, including:

- Availability and type of electron acceptors
- Moisture content
- Soil pH
- Soil temperature
- Nutrient supply
- Contaminant concentration
- Bioavailability and relative biodegradation

Each of these parameters was measured at Bioventing Initiative sites. The actual effect of individual parameters on microbial activity is difficult to assess in the field because of interference and interactions among these parameters. The in situ respiration test was used as a measurement tool that integrates all factors to assess whether the microorganisms are metabolizing the fuel. Data from the in situ respiration test and site measurements were used to conduct a statistical analysis of the observed effects of the site measurements on microbial activity in the field. The statistical analysis was constructed to account for parameter interactions. These results are discussed in detail in Chapter 5. A more general discussion of the significance of each of these parameters and its effect on microbial activity is provided in Sections 3.3.2.1 through 3.3.2.7.

3.2.2.1 Electron Acceptor Conditions

One of the most important factors influencing the biodegradability of a compound is the type and availability of electron acceptors. Following a hydrocarbon spill, for example, the microbial degradation of biodegradable hydrocarbons results in oxygen depletion and thus anaerobic conditions in the subsurface soil. Although hydrocarbons may undergo limited biodegradation under anaerobic conditions (Bilbo et al., 1992; Mormile et al., 1994), aerobic conditions generally are most suitable for relatively rapid remediation of petroleum hydrocarbons. Therefore, oxygen supply is crucial to the success of a bioventing system. In field studies, oxygen has been found to be the most important factor in determining the success of a bioventing system (Hinchee et al., 1989; Miller et al., 1991). The Bioventing Initiative confirmed this conclusion, finding that oxygen was the primary factor limiting microbial activity at all but three sites (Miller et al., 1993).

3.2.2.2 Moisture Content

Soil moisture content may affect the bioventing process by its effect on microorganisms or soil gas permeability. Microorganisms require moisture for metabolic processes and for solubilization of energy and nutrient supplies. Conversely, soil moisture content directly affects soil permeability, with high moisture content resulting in poor distribution of oxygen. In practice, soil moisture has been found to directly limit biodegradation rates only where bioventing has been implemented in very dry desert environments. A more common influence of moisture is that excess moisture has led to significant reductions in soil gas permeability. One major objective of the Bioventing Initiative was to assess the effects of moisture on biodegradation.

The range of soil moisture content measured at Bioventing Initiative sites is shown in Figure 3-4. The lowest soil moisture content measured was 2 percent by weight, and microbial activity still was observed in these soils. Figure 3-5 illustrates the observed relationship between soil moisture and oxygen utilization rates. To date, a strong correlation has not been recorded between moisture content and oxygen utilization rate, although a slight positive relationship has been observed.[5]

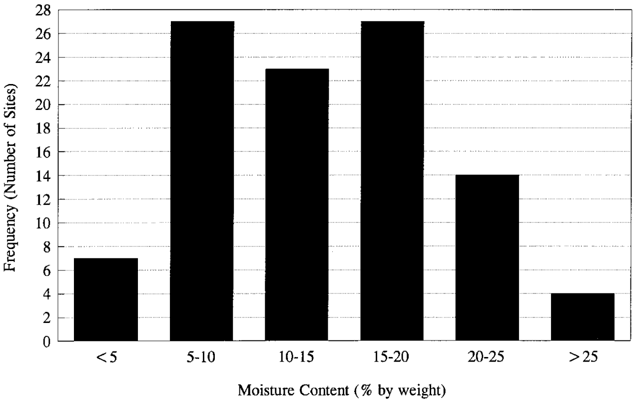


Figure 3-4. Soil moisture content measurements at Bioventing Initiative sites.

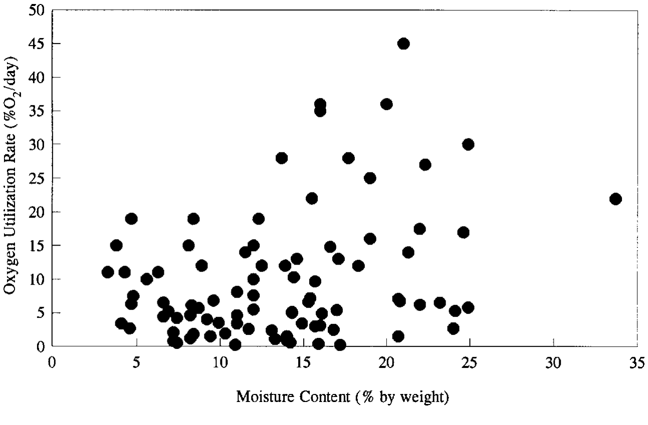


Figure 3-5. Direct correlation between oxygen utilization rates and soil moisture content at Bioventing Initiative sites.

---

[5] See Section 5.2 for a discussion of the statistical relationship between moisture content and oxygen utilization rates.

At a desert site at the Marine Corps Air Ground Combat Center, Twentynine Palms, California, soil moisture content appeared to detrimentally affect microbial activity. Soil moisture content ranged from 2 percent to 4 percent by weight and, although the site was contaminated with jet fuel, significant oxygen limitation was not observed. An irrigation system was installed at the site in an effort to enhance microbial activity. The site was irrigated for 1 week, then bioventing was initiated for 1 month before conducting an in situ respiration test. In situ respiration rates measured after irrigation were significantly higher than those measured before irrigation (Figure 3-6). In addition, before irrigation, oxygen was not consumed below approximately 17 percent before microbial activity stopped. After irrigation, activity continued until oxygen was completely consumed to less than 1 percent. These results demonstrated that in extreme cases, moisture addition may improve the performance of bioventing systems through enhanced microbial activity.

Air injection bioventing may dry out the soil to a point that would be detrimental to microbial growth, necessitating humidification of the injection air. A simple calculation, however, as shown in Example 3-1, illustrates that moisture loss is minimal over a 3-year period. Drying and moisture loss as a result of bioventing usually are only a problem very near the vent well or if very high air injection rates are used (typically not the case in properly designed bioventing systems). Sites typically have several moisture sources that also make drying due to air injection negligible, such as rain and snow, and water as a by-product of mineralization (generated at a rate of 1.5 kg of water for every 1 kg of hydrocarbon degraded).[6]

Example 3-1. Moisture Content Change During Air Injection and Water Generated During Biodegradation: For this test:

Vapor pressure (P_{water}) = 17.5 mm Hg
Flow rate (Q) = 1 pore volume/day (typical of bioventing)
Volume of treatment area (V) = 12,300 m^3
Biodegradation rate (k_B) = 3 mg/kg-day
Initial moisture content = 15 percent by weight
Soil bulk density = 1,440 kg/m^3

Assume worst case of 0 percent humidity and no infiltration.

To calculate the total water at the site initially, the mass of soil is first calculated:

$$12{,}300\ m^3 \times \frac{1{,}440\ kg}{m^3} = 1.8 \times 10^7\ kg\ soil$$

Therefore, the initial mass of water is:

$$(1.8 \times 10^7\ kg\ soil) \times 0.15 = 2.7 \times 10^6\ kg\ H_2O$$

Because the flow rate is equivalent to 1 pore volume/day, the mass of water removed per day will be equal to the mass of water in the vapor phase of the treated area, which can be calculated using the Ideal Gas Law:

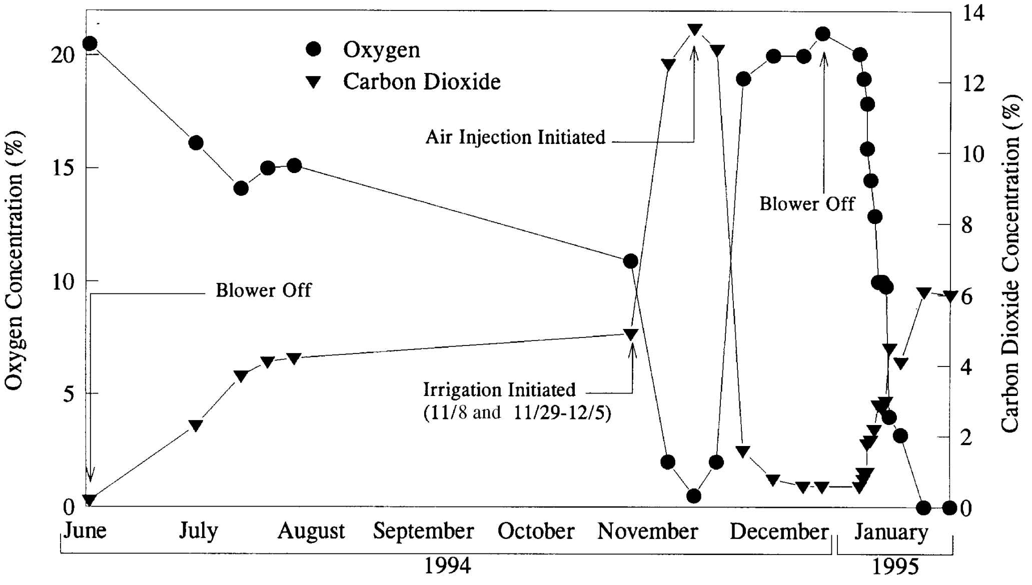


Figure 3-6. Oxygen and carbon dioxide concentrations before and after irrigation at Twentynine Palms, California.

---

[6] See Equation 3-7 for the stoichiometry of this calculation.

Total water removal in 3 years:

$$\frac{\text{Moles } H_2O \text{ removed}}{\text{day}} = \frac{P_{\text{water}}\, V}{RT} =$$

$$\frac{17.5 \text{ mm Hg} \times 12{,}300 \text{ m}^3}{\left(0.0623 \, \frac{\text{m}^3\text{-mm Hg}}{\text{mole-°K}}\right) \times 298\text{°K}}$$

$$\frac{\text{Moles } H_2O \text{ removed}}{\text{day}} = 11{,}600 = 210 \, \frac{\text{kg}}{\text{day}}$$

$$210 \, \frac{\text{kg}}{\text{day}} \times 1{,}095 \text{ days} = 230{,}000 \text{ kg removed}$$

This water loss represents a fairly small percentage, or:

$$\frac{230{,}000 \text{ kg evaporated}}{2.7 \times 10^6 \text{ initial mass}} = 0.086 \approx 8.6\% \; H_2O \text{ loss}$$

This is equivalent to a soil moisture drop from approximately 15 percent to 13.7 percent. Assuming a contaminated thickness of 10 ft (3 m), an infiltration rate of approximately 2.4 inches (6.1 cm) in 3 years, or less than 1 inch (2.5 cm) per year, would replace the lost moisture. In practice, some drying very close to the vent well may be observed but usually is not.

Water loss also will be replaced through biodegradation of hydrocarbons. Calculating the total mass of hydrocarbons degraded over 3 years:

$$3 \, \frac{\text{mg}}{\text{kg-day}} \times 1{,}095 \text{ days} \times (1.8 \times 10^7 \text{ kg soil}) \times$$

$$\frac{\text{kg}}{10^6 \text{mg}} = 59{,}000 \text{ kg hydrocarbon degraded}$$

Based on the stoichiometry in Equation 2-1, if 1.5 kg of water are generated for every kg of hydrocarbon degraded, the amount of water generated would be:

$$59{,}000 \text{ kg hydrocarbon} \times \frac{1.5 \text{ kg water}}{\text{kg hydrocarbon}} =$$

$$88{,}500 \text{ kg water}$$

Therefore, total water removal in 3 years must also account for the water generation, where:

$$230{,}000 \text{ kg} - 88{,}500 \text{ kg } H_2O = 141{,}500 \text{ kg } H_2O \text{ loss}$$

This is equivalent to a water loss of 5.3 percent over 3 years.

3.2.2.3 Soil pH

Soil pH also may affect the bioremediation process because microorganisms require a specific pH range to survive. Most bacteria function best in a pH range between 5 and 9 with the optimum being slightly above 7 (Dragun, 1988). A shift in pH may result in a shift in the makeup of the microbial population because each species exhibits optimal growth at a specific pH. Throughout the Bioventing Initiative, pH has not been found to limit in situ bioremediation and is probably only of concern where contamination has radically altered the existing pH.

Figure 3-7 illustrates the range of soil pH found at the Bioventing Initiative sites to date. In general, the majority of sites have fallen within the “optimal” pH range for microbial activity of 5 to 9. Microbial respiration based on oxygen utilization has been observed at all sites, however, even in soils where the pH was below 5 or above 9. Figure 3-8 illustrates the observed relationship between pH and oxygen utilization rates. These observations suggest that pH is not a concern when bioventing at most sites.[7]

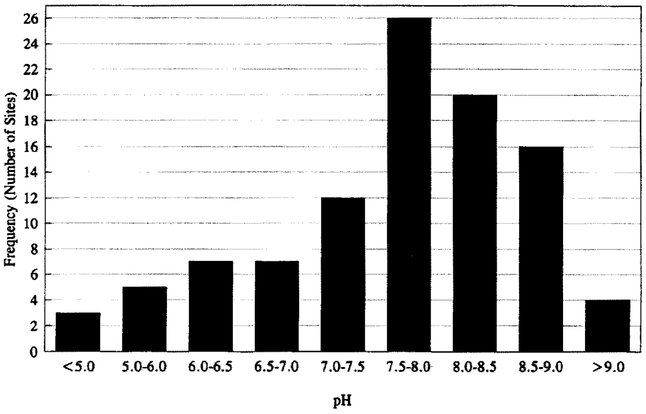


Figure 3-7. Soil pH measurements at Bioventing Initiative sites.

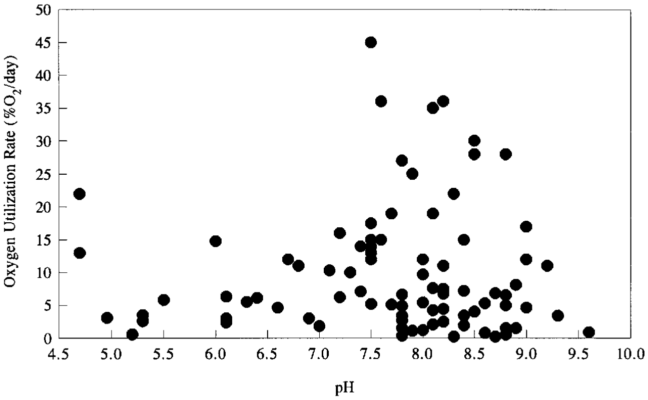


Figure 3-8. Correlation between oxygen utilization rate and soil pH at Bioventing Initiative sites.

---

[7] See Section 5.2 for a discussion of the statistical relationship between pH and oxygen utilization rates.

3.2.2.4 Soil Temperature

Soil temperature may significantly affect the bioremediation process. Microbial activity has been reported at temperatures varying from -12°C to 100°C (10°F to 212°F) (Brock et al., 1984); however, the optimal range for biodegradation of most contaminants is generally much narrower. An individual microorganism may tolerate a temperature peak of up to approximately 40°C (104°F). A microorganism's optimal growth temperature, however, varies depending on climate. For example, microorganisms in a subarctic environment may exhibit optimal growth at 10°C (50°F), whereas microorganisms in a subtropical environment may exhibit optimal growth at 30°C (86°F).

Generally biodegradation rates double for every 10°C (50°F) temperature increase, up to some inhibitory temperature. The van't Hoff-Arrhenius equation expresses this relationship quantitatively as:

$$k_T = k_o\, e^{\frac{-E_a}{RT_{abs}}} \qquad \text{(Eq. 3-9)}$$

where:

k_T = temperature-corrected biodegradation rate (percentage of O_2/day)

k_o = baseline biodegradation rate (percentage of O_2/day)

E_a = activation energy (cal/mole)

R = gas constant (1.987 cal/°K-mol)

T_{abs} = absolute temperature (°K)

Miller (1990) found E_a equal to 8 to 13 kcal/mole for in situ biodegradation of jet fuel. In the 17°C to 27°C (63°F to 81°F) range, the van't Hoff-Arrhenius relationship accurately predicted biodegradation rates. A similar analysis was conducted at Site 20, Eielson AFB, Alaska, where the activation energy was found to be equal to 13.4 kcal/mole (Example 3-2). Figure 3-9 illustrates the relationship between oxygen utilization rate and temperature and between biodegradation and temperature observed at Site 20, Eielson AFB, a JP-4 jet fuel-contaminated site.

Example 3-2. Calculation of the van't Hoff-Arrhenius Constant From Site Data: Various forms of soil warming were tested at Site 20, Eielson AFB, Alaska. This resulted in a wide range of temperatures and biodegradation rates measured at the same site.

To calculate the van't Hoff-Arrhenius constant, the log of the biodegradation rate must be calculated versus the inverse of the temperature to provide the relationship:

$$\ln\left(\frac{k_T}{K_O}\right) = \frac{-E_a}{R} \times \frac{1}{T}$$

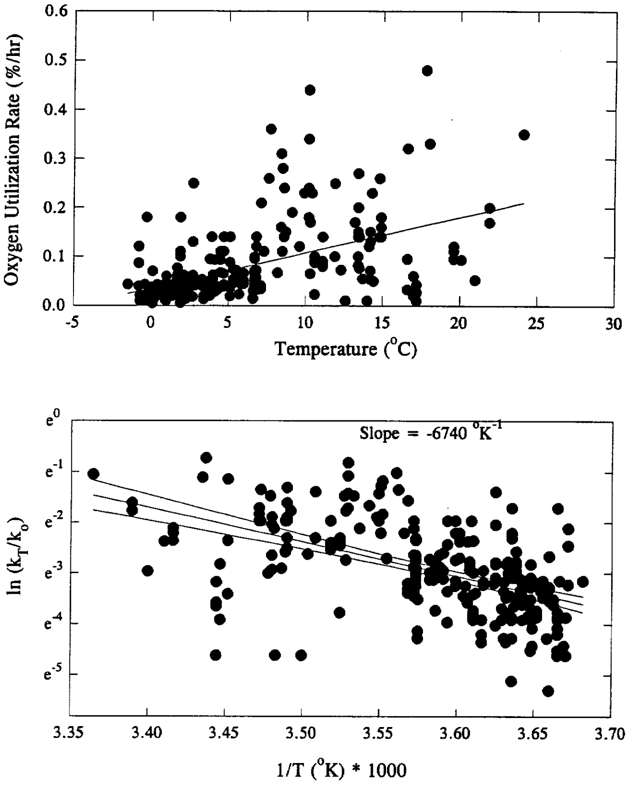


Figure 3-9. **Soil temperature versus oxygen utilization and biodegradation rate at Site 20, Eielson AFB, Alaska.**

The slope of the linear regression of inverse temperature versus oxygen utilization rate is -6,740 °K (Figure 3-9). Therefore,

$$\frac{E_a}{R} = -6{,}740$$

$$\frac{E_a}{1.987\,\frac{\text{cal}}{\text{°K-mole}}} = -6{,}740$$

$$E_a = 1.987\,\frac{\text{cal}}{\text{°K-mole}} \times -6{,}740 =$$

$$13{,}390\,\frac{\text{cal}}{\text{mole}} \approx 13.4\,\frac{\text{kcal}}{\text{mole}}$$

Heat addition may improve bioventing processes. Solar warming, warm water infiltration, and buried heat tape have been used to increase soil temperature. Their use has increased microbial activity and contaminant degradation (Leeson et al., 1995). Selection of a soil warming technique depends on a comparison of cost considerations versus remediation time requirements.[8] Although

---

[8] See Section 4.4 for a discussion of the cost benefit of soil warming.

warm water infiltration or heat tape can significantly increase biodegradation rates, the cost is significantly higher than simply using surface insulation or no heating method. The use of warm water infiltration, although effective, is limited to very permeable soils to ensure that adequate drainage of the applied water occurs. The use of soil heating to increase biodegradation rates may only prove cost-effective in cold regions, such as Alaska.

3.2.2.5 Nutrient Supply

To sustain microbial growth, certain nutrients must be available at minimum levels. The following nutrients/cofactors are known to be required in order to support microbial growth: calcium, cobalt, copper, iron, magnesium, manganese, molybdenum, nitrogen, phosphorus, potassium, sodium, sulfur, and zinc. Nitrogen and phosphorus are required in the greatest concentrations and are the nutrients most likely to limit microbial growth. The remaining chemicals are considered micronutrients because they are required in only small quantities and generally are available in excess in nature.

Nutrients are required as components of the microbial biomass. The need for these nutrients is very different from the need for oxygen (or other electron donors) and the carbon source. Nutrients are not destroyed but are recycled by the ecosystem. Thus, unlike oxygen, a steady input of nutrient is not required.

An approach to estimation of nutrient requirements, suggested by John T. Wilson of the EPA Ada Laboratory, can be made based on microbial kinetics. Starting with:

$$\frac{dX}{dt} = K_b\,Y - K_d\,X \qquad \text{(Eq. 3-10)}$$

where:

X = biomass (mg biomass/kg soil)
k_B = biodegradation rate (mg hydrocarbon/kg soil-day)
Y = cell yield (mg biomass/mg hydrocarbon)
k_d = endogenous respiration rate (day^{-1})

Assuming that the biomass concentration achieves steady state during bioventing,

$$\frac{dX}{dt} = 0 = K_b\,Y - K_d\,X \qquad \text{(Eq. 3-11)}$$

Solving:

$$X = \frac{K_b\,Y}{Kd} \qquad \text{(Eq. 3-12)}$$

Little is known about the in situ cell yields or endogenous respiration rates of hydrocarbon-degrading organisms, but these parameters can be estimated based on ranges reported in the wastewater treatment literature (Metcalf and Eddy, 1979). An example for calculating required nutrients is shown in Example 3-3.

Example 3-3. Estimation of Nutrient Requirements in Situ: For a given site, the following is assumed:

k_B = 10 mg/kg-day (typical rate found at bioventing sites)
Y = 0.5 mg/mg
k_d = 0.05/day

Solving:

$$X = \frac{10\,\frac{mg}{kg\text{-}day} \times 0.5\,\frac{mg}{mg}}{\frac{0.05}{day}} = 100\,\frac{mg}{kg}$$

To sustain 100 mg/kg of biomass, the nutrient requirements may be estimated from biomass to nutrient ratios. A variety of ratios is found in the literature. For this example, a 100:10:1 ratio of biomass:nitrogen:phosphorus is assumed. This ratio yields a nutrient requirement of 10 mg/kg of nitrogen and 1 mg/kg of phosphorus. Thus, if the above assumptions hold, a site with at least these levels of nitrogen and phosphorus initially should not be rate-limited by nitrogen and phosphorus.

Most soils naturally contain nutrients in excess of the concentrations calculated in Example 3-3. Therefore, although the addition of nutrients may be desirable in hopes of increasing biodegradation rates, field research to date does not indicate the need for these additions (Dupont et al., 1991; Miller et al., 1991). Therefore, although nutrients are often added to bioremediation projects in anticipation of increased biodegradation rates, field data to date do not show a clear relationship between increased rates and supplied nutrients.

Concentrations of total Kjeldahl nitrogen (TKN) and total phosphorus at the Bioventing Initiative sites and

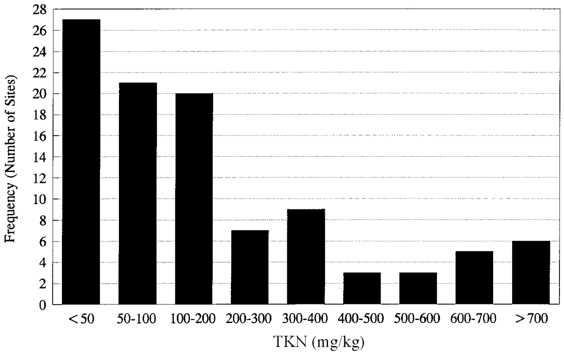


Figure 3-10. TKN measurements at Bioventing Initiative sites.

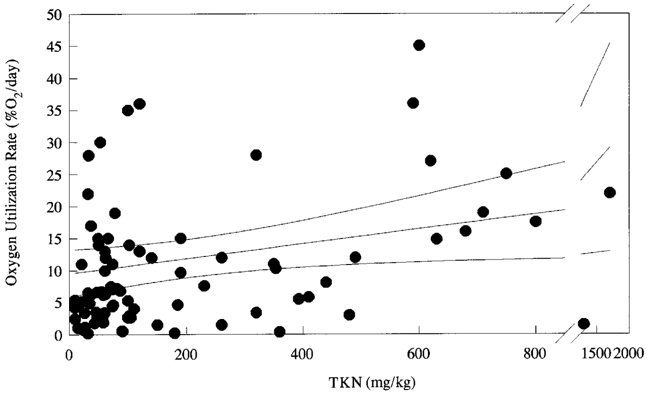


Figure 3-11. **Correlation between oxygen utilization rate and TKN at Bioventing Initiative sites.**

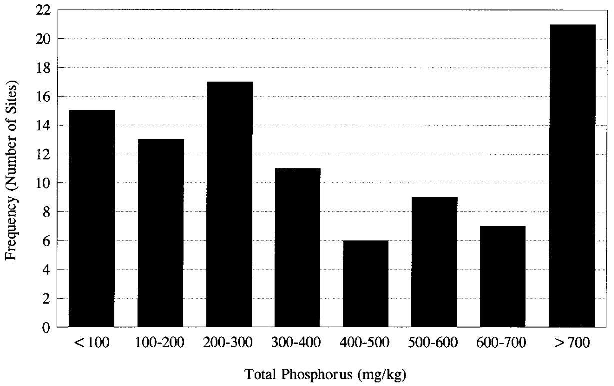


Figure 3-12. **Total phosphorus measurements at Bioventing Initiative sites.**

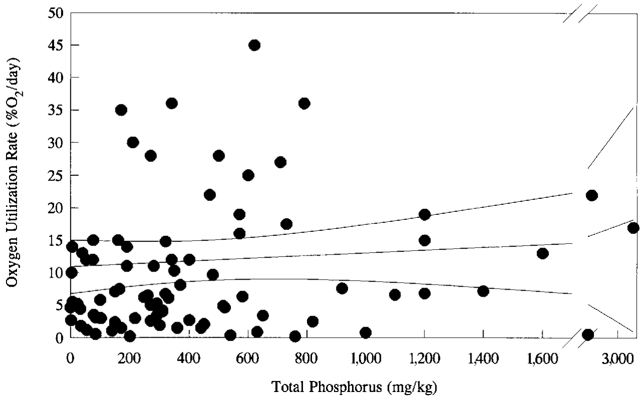


Figure 3-13. **Correlation between oxygen utilization rate and total phosphorus at Bioventing Initiative sites.**

the corresponding relationship between oxygen utilization rates are shown in Figures 3-10 through 3-13. Although optimal ratios of carbon, nitrogen, and phosphorus were not available at all sites, the natural nutrient levels were sufficient to sustain some level of biological respiration at all sites when the most limiting element, oxygen, was provided.

In controlled nutrient additions at Tyndall and Hill AFBs,[9] no apparent increase in microbial activity was observed. Therefore, there appeared to be no benefit of nutrient addition. The relationship between oxygen utilization rates and TKN and total phosphorus are shown in Figures 3-11 and 3-13, respectively. As illustrated in these figures, no correlation exists between phosphorus and oxygen utilization rates and only a weak relationship exists between TKN concentrations and oxygen utilization rates, again emphasizing that natural ambient nutrient levels seem sufficient for microbial activity.[10]

Figure 3-14 illustrates the range of iron concentrations measured at Bioventing Initiative sites. Iron concentrations varied greatly, with concentrations from less than 100 mg/kg to greater than 75,000 mg/kg. Soils in Hawaii and Alaska exhibited the highest iron contents. Although iron is a nutrient required for microbial growth, iron also may react with oxygen to form iron oxides. Theoretically, if a significant amount of iron oxidation occurs, the observed oxygen utilization rate[11] would not reflect microbial activity only. Calculated biodegradation rates would therefore be an overestimate of actual biodegradation rates. Thus, background wells in uncontaminated areas are recommended in bioventing applications in areas of high iron concentrations. To date, this study has shown no correlation between iron content and oxygen utilization rates (Figure 3-15).

3.2.2.6 Contaminant Concentration

Contaminant concentration also may affect biodegradation of the contaminant itself. Excessive quantities of a

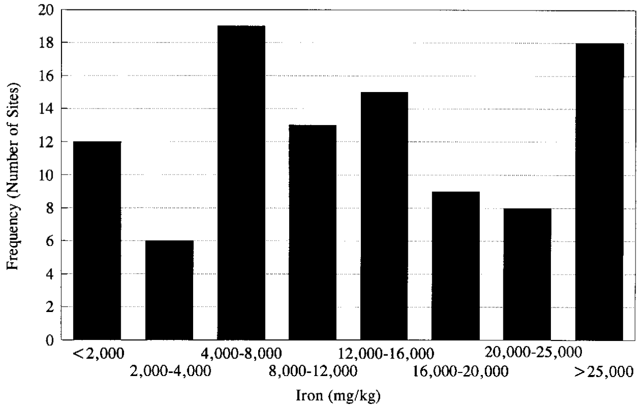


Figure 3-14. **Iron concentration measurements at Bioventing Initiative sites.**

---

[9] See Sections 4.1 and 4.2 for a detailed discussion of these sites.

[10] See Section 5.2 for a discussion of the statistical relationship between nutrients and oxygen utilization rates.

[11] As measured by in situ soil gas oxygen concentrations.

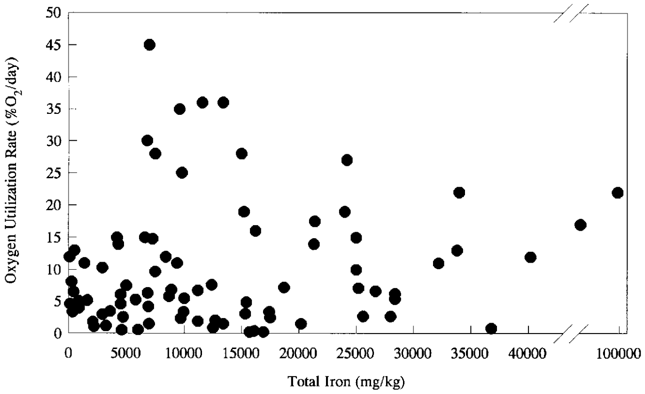


Figure 3-15. **Correlation between oxygen utilization rates and iron content at Bioventing Initiative sites.**

contaminant can result in a reduction in biodegradation rate because of a toxicity effect. Conversely, very low concentrations of a contaminant also may reduce overall degradation rates because contact between the contaminant and the microorganism is limited and the substrate concentration is likely below S_{min}.

In practice, petroleum hydrocarbons in fuel mixtures do not generally appear to be toxic to the bioventing process. Other more soluble compounds (i.e., phenolics) or less biodegradable compounds (i.e., TCE) may exhibit a toxicity effect, and reports indicate that pure benzene may be toxic. Although a general relationship between bioventing rates and concentration no doubt exists, the relationship is complex and not fully understood. At sites where NAPLs are present (soil concentrations above the 100 to 1,000 mg/kg range), the bioavailable hydrocarbon is most probably limited by solubilization, which is linked to Raoult's Law and, to an extent, is independent of total hydrocarbon concentration. Certainly, the NAPL distribution can affect the proportion of the soil in a site in which biodegradation is occurring, and at lower concentrations, less soil may be in direct contact with NAPLs. The reduction in biodegradation rates observed over time on many sites is likely caused, at least in part, by changes in the hydrocarbon makeup as more degradable and more mobile compounds (i.e., benzene, toluene, ethylbenzene, and xylenes) are removed. At lower hydrocarbon concentrations where NAPLs are not present, a decline in rate would be expected with time as the available substrate is removed.

3.2.2.7 Bioavailability and Relative Biodegradability

Another important parameter affecting the extent of in situ bioremediation is bioavailability of the contaminant(s) of concern. Bioavailability is a term that describes the accessibility of contaminants to the degrading populations. Bioavailability consists of (1) a physical aspect related to phase distribution and mass transfer and (2) a physiological aspect related to the suitability of the contaminant as a substrate (U.S. EPA, 1993). Compounds with greater aqueous solubilities and lower affinities to partition into NAPL or to sorb onto the soil generally are bioavailable to soil microorganisms and are more readily degraded. For example, BTEX compounds are preferentially degraded relative to the larger alkanes found in fuels. The most likely explanation for this is that BTEX compounds are more mobile and more soluble in pore water and therefore are more bioavailable.

3.3 Compounds Targeted for Removal

Any aerobically biodegradable compound, such as petroleum hydrocarbons, potentially can be degraded though bioventing. To date, bioventing has been applied primarily to petroleum hydrocarbons (Table 2-2); however, bioventing of PAHs (Lund et al., 1991; Hinchee and Ong, 1992; EPA, 1994a; Alleman et al., 1995) and bioventing applied to an acetone, toluene, and naphthalene mixture (Leeson et al., 1994) have been implemented successfully.

The key to bioventing feasibility in most applications is biodegradability versus volatility of the compound. If the rate of volatilization greatly exceeds the rate of biodegradation, bioventing is unlikely to be successful because removal occurs primarily though volatilization. This will occur most often in cases where the contaminant is a fresh, highly volatile fuel. An unsuccessful bioventing application is unlikely to occur due to a lack of microbial activity. If bioventing is operated in an injection mode, as this manual recommends, volatilized contaminants may be biodegraded before reaching the surface, unlike during an extraction operation.[12] Figure 3-16 illustrates the relationship between a compound's physicochemical properties and its potential for bioventing.

In general, compounds with a low vapor pressure[13] cannot be successfully removed by volatilization but can be biodegraded in a bioventing application if they are aerobically biodegradable. High vapor pressure compounds are gases at ambient temperatures. These compounds volatilize too rapidly to be easily biodegraded in a bioventing system but are typically a small component of fuels and, because of their high volatility, they will attenuate rapidly. Compounds with vapor pressures between 1 and 760 mm Hg may be amenable to either volatilization or biodegradation. Within this intermediate

---

[12] See Section 2.1 of Volume II for a discussion of air injection versus extraction considerations.

[13] For the purposes of this discussion, compounds with vapor pressures below approximately 1 mm Hg are considered low, and compounds with vapor pressures above approximately 760 mm Hg are considered high.

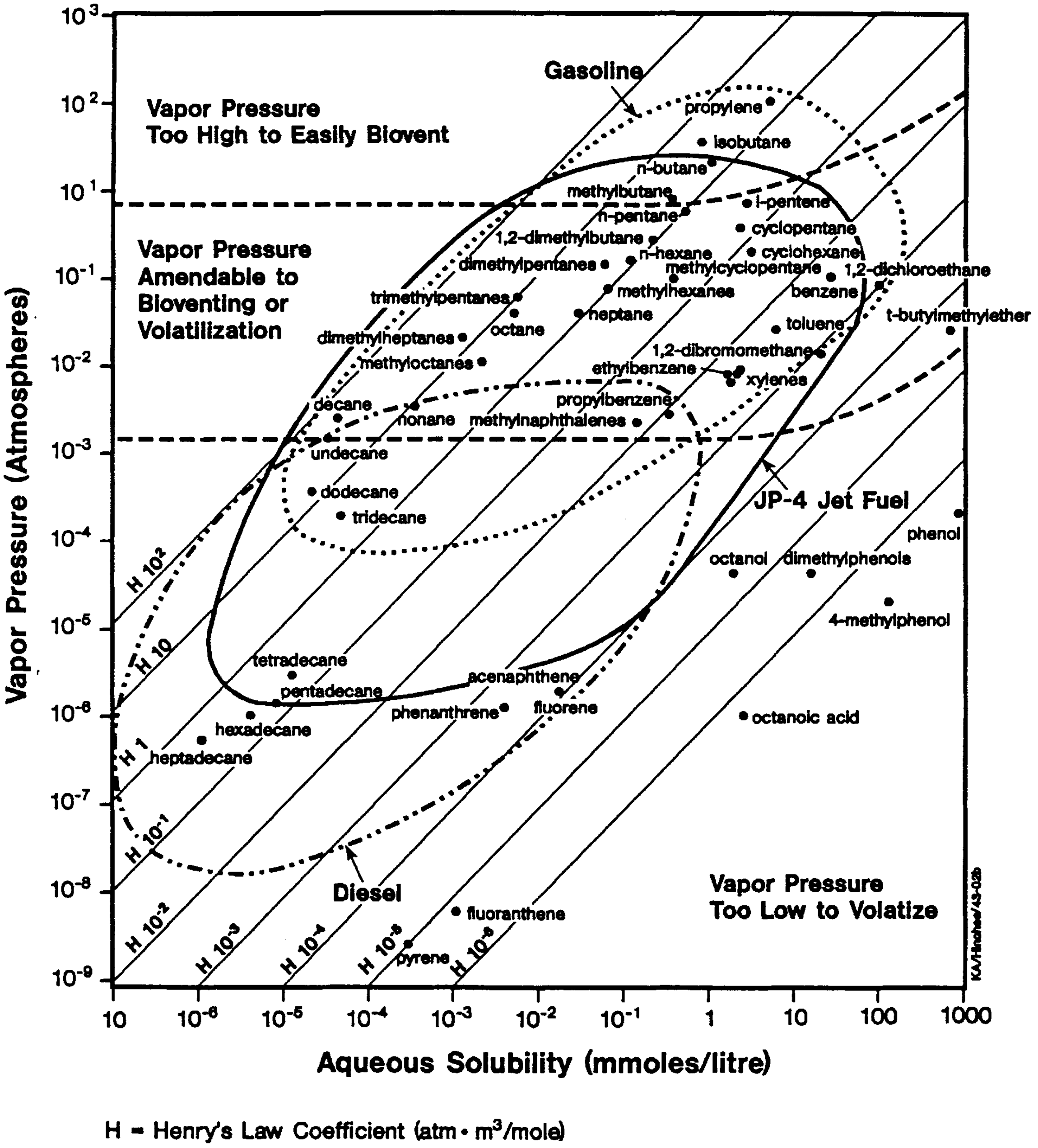


Figure 3-16. Relationship between contaminant physicochemical properties and potential for bioventing.

range lie many of the petroleum hydrocarbon compounds of greatest regulatory interest, such as benzene, toluene, ethylbenzene, and xylenes. As can be seen in Figure 3-16, various petroleum fuels are more or less amenable to bioventing. Some components of gasoline are too volatile to biodegrade easily but, as stated previously, are typically present in low overall concentrations and are attenuated rapidly. Most of the diesel constituents are sufficiently nonvolatile to preclude volatilization, whereas the constituents of JP-4 jet fuel are intermediate in volatility.

To be amenable to bioventing, a compound must (1) biodegrade aerobically at a rate resulting in an oxygen demand greater than the rate of oxygen diffusion from the atmosphere and (2) biodegrade at a sufficiently high rate to allow in situ biodegradation before volatilization. Practically, this means that low vapor pressure compounds need not biodegrade as rapidly as high vapor pressure compounds for bioventing to be successful. Figure 3-17 illustrates this relationship. The actual feasibility of bioventing is very site-specific, so Figures 3-16 and 3-17 should be used as general guidelines rather than absolutes.

Bioventing generally is not considered appropriate for treating compounds such as polychlorinated biphenyls (PCBs) and chlorinated hydrocarbons. Through a

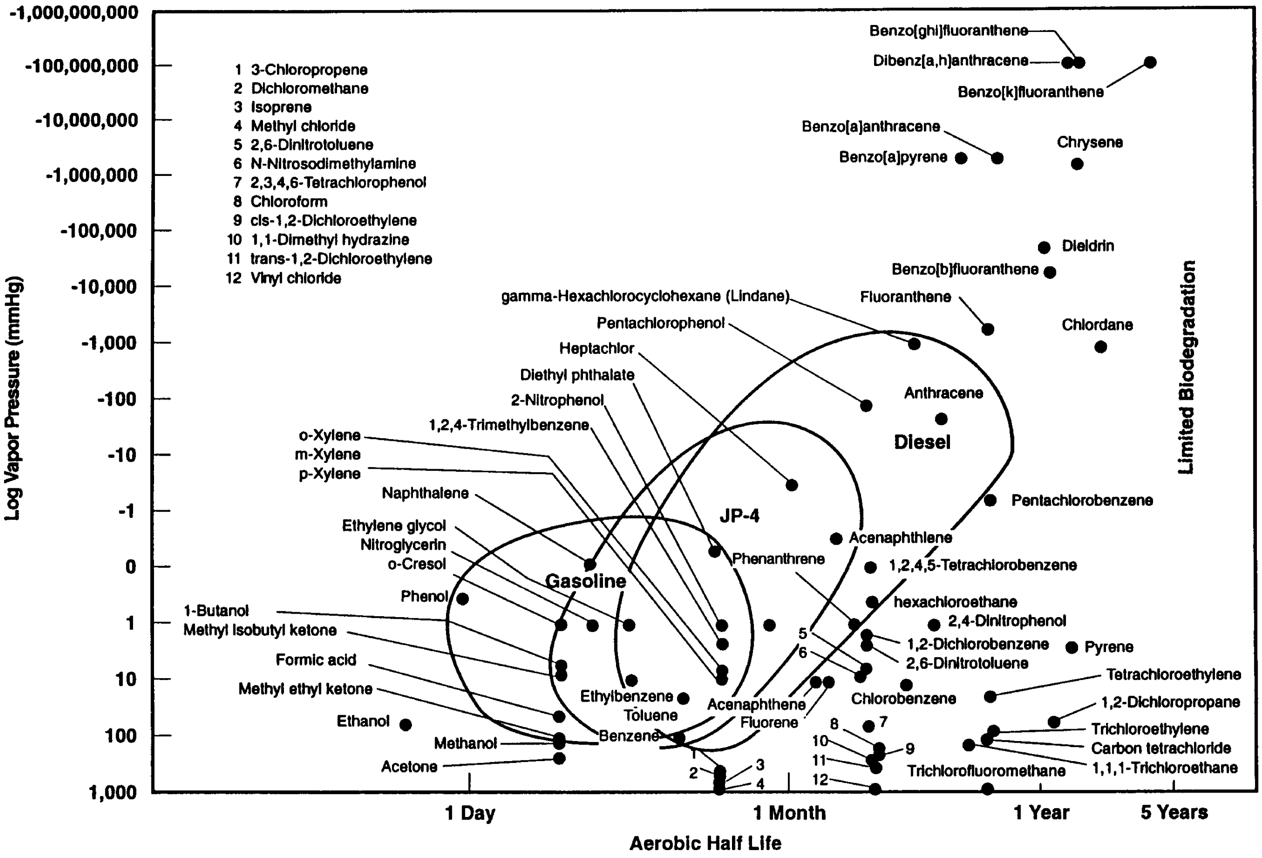


Figure 3-17. Relationship between contaminant pressure and aerobic biodegradability.

cometabolic process, however, enhancement of the degradation of compounds such as TCE through bioventing may be possible. Laboratory studies have shown that if toluene is present to provide the primary source of carbon, organisms that grow on toluene may be able to cometabolize TCE (Wackett and Gibson, 1992). More recently, Hopkins et al. (1993) demonstrated TCE degradation in situ through the injection of oxygen and phenol into an aquifer. TCE removal of 88 percent was observed in the field, indicating the potential for cometabolic degradation of chlorinated compounds in situ.

3.4 BTEX Versus TPH Removal in Petroleum-Contaminated Sites

In many areas, treatment of petroleum hydrocarbons is based on BTEX compounds. Typically, these compounds degrade rapidly during bioventing and, at most sites, degrade to below detection limits within 1 year of operation of a bioventing system. This trend was illustrated in a study at Tyndall AFB[14] and has been confirmed at 81 sites completing the 1-year testing under the Bioventing Initiative. At Tyndall AFB, two test plots were studied with initial hydrocarbon concentrations of 5,100 and 7,700 mg/kg. After 9 months of bioventing, TPH decreased by 40 percent from the initial concentration. Low-molecular-weight compounds such as BTEX, however, decreased by more than 90 percent (Figure 3-18). Low-molecular-weight compounds were preferentially degraded over heavier fuel components, which is consistent with previous research (Atlas, 1986).

If a risk-based approach to remediation is used that focuses on removing the soluble, mobile, and more toxic BTEX components of the fuel, remediation times can be significantly reduced, making bioventing an attractive technology for risk-based remediations. In addition, Bioventing Initiative results illustrate that BTEX compounds often initially are relatively low at many fuel-contaminated sites. Data collected from the majority of the Bioventing Initiative sites demonstrate that more than 85 percent of initial soil samples contained less than 1 mg/kg of benzene (Figure 3-19). An exception to this may be gasoline-contaminated sites; the majority of sites included in the Bioventing Initiative were contaminated with heavier weight contaminants. Only 19 of 125 Bioventing Initiative sites were contaminated by gasoline or aviation gas (AVGAS).

---

[14] See Section 4.2 for a case history of the bioventing study at Tyndall AFB, Florida.

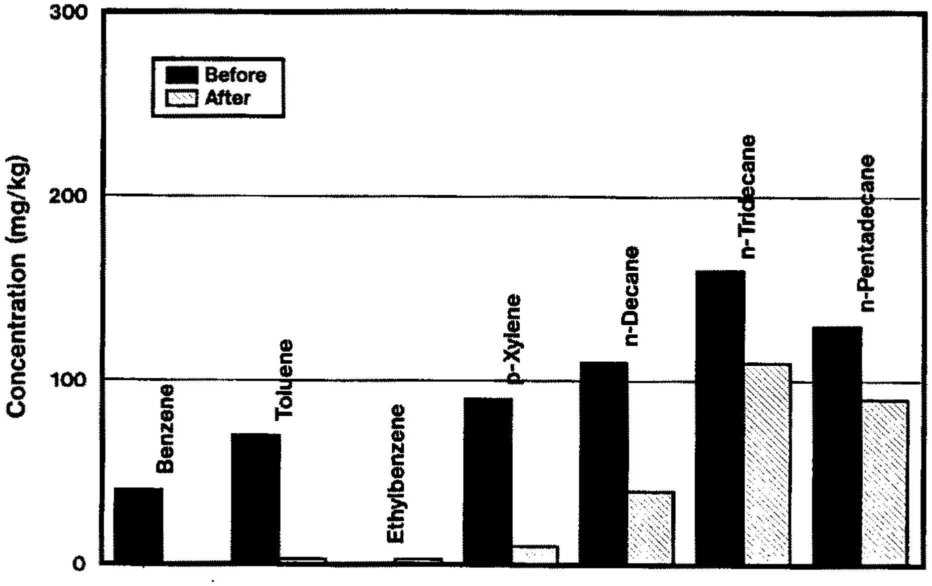


Figure 3-18. Results of soil analysis before and after venting from Plot V2 at Tyndall AFB, Florida.

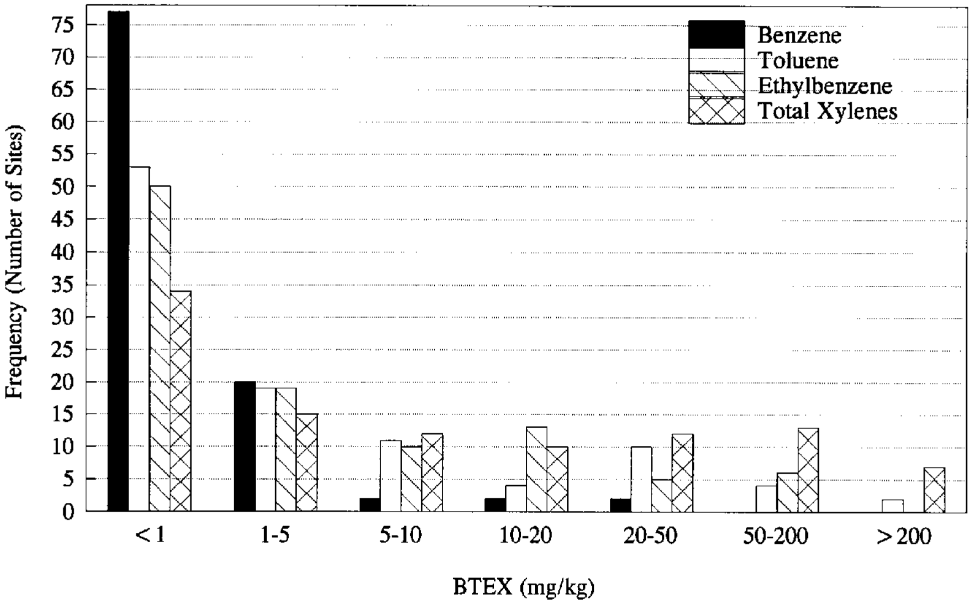


Figure 3-19. Contaminant distribution at Bioventing Initiative sites.

Chapter 4
Bioventing Case Histories

Four of the first well-documented bioventing studies are presented in this chapter to illustrate significant results that have contributed to the development of bioventing, the Bioventing Initiative, and this document. The development of the Bioventing Initiative was largely based upon the results from these four early studies. Site 914, Hill AFB, Utah, was one of the first bioventing systems studied. This study was designed to examine the feasibility of biodegradation through air injection and also to investigate the effect of nutrient and moisture addition on biodegradation. The second site was a bioventing system at Tyndall AFB, Florida, initiated in 1990. This study was short-term (9 months) but was designed to examine process variables in more detail than was possible at Site 914, Hill AFB. The third site discussed in this chapter was conducted at Site 280, Hill AFB, Utah. This study was initiated in 1991 as a bioventing site and was operated for approximately 3 years. Research on air flow rates and injection depth was conducted at this site. The fourth study presented in this chapter was conducted at Eielson AFB, Alaska. This study was initiated in 1991 as a bioventing system and was operated for 3 years. This study was conducted to examine the feasibility of bioventing in a subarctic climate and to evaluate the effects of soil warming on biodegradation rates.

A case history of the Fire Training Area, Battle Creek Air National Guard Base (ANGB), Michigan, also is presented in this chapter. This site was included in the Bioventing Initiative, but additional samples were collected at the end of the 1-year study as part of a separate project. The results from this study illustrate typical installations and results from a Bioventing Initiative site and provide additional data on BTEX contamination after 1 year of bioventing.

These case histories are not presented as design examples because these studies were designed as research efforts. In fact, these studies have been the basis for development of current design practice as presented in Volume II of this document. Details of each study are presented in the following sections.

4.1 Site 914, Hill AFB, Utah

A spill of approximately 27,000 gal of JP-4 jet fuel occurred at Site 914 when an automatic overflow device failed. Contamination was limited to the upper 65 ft (20 m) of a delta outwash of the Weber River. This surficial formation extends from the surface to a depth of approximately 65 ft (20 m) and comprises mixed sand and gravel with occasional clay stringers. Depth to regional ground water is approximately 600 ft (180 m); however, water occasionally may be found in discontinuous perched zones. Soil moisture averaged less than 6 percent by weight in the contaminated soils.

The collected soil samples had JP-4 jet fuel concentrations of up to 20,000 mg/kg, with an average concentration of approximately 400 mg/kg (Oak Ridge National Laboratory, 1989). Contaminants were unevenly distributed to depths of 65 ft (20 m). Vent wells were drilled to approximately 65 ft (20 m) below the ground surface and were screened from 10 to 60 ft (3 to 20 m) below the surface. A background vent well was installed in an uncontaminated location in the same geological formation approximately 700 ft (210 m) north of the site.

This system originally was designed for SVE, not bioventing. During the initial 9 months of operation, it was operated to optimize volatilization, while biodegradation was merely observed. After this period, air flow rates were greatly reduced, and an effort was made to optimize biodegradation and limit volatilization.

Soil vapor extraction was initiated in December 1988 at a rate of approximately 25 cubic ft per minute (cfm) (710 L/min). The off-gas was treated by catalytic incineration, and initially the highly concentrated gas needed to be diluted to keep it below explosive limits and within the incinerator's hydrocarbon operating limits. The venting rate was gradually increased to approximately 1,500 cfm (4.2×10^4 L/min) as hydrocarbon concentrations dropped. During the period between December 1988 and November 1989, more than 3.5×10^8 ft^3 (9.9×10^{10} L) of soil gas were extracted from the site.

In November 1989, ventilation rates were reduced to between approximately 300 cfm and 600 cfm (8,500 to 17,000 L/min) to provide aeration for bioremediation while reducing off-gas generation. This change allowed removal of the catalytic incinerators, saving approximately $13,000 per month in rental and propane costs.

Hinchee and Arthur (1991) conducted bench-scale studies using soils from this site and found that, in the laboratory, both moisture and nutrients appeared to become limiting after aerobic conditions had been achieved. These findings led to the addition of first moisture and then nutrients in the field. Moisture addition clearly stimulated biodegradation; nutrient addition did not (Figure 4-1). The failure to observe an effect of nutrient addition could be explained by many factors, including that the nutrients failed to move in the soils, which is a problem particularly for ammonia and phosphorus (Aggarwal et al., 1991); remediation of the site was entering its final phase and nutrient addition may have been too late to result in an observed change; and/or nutrients simply may have not been limiting.

During extraction, oxygen and hydrocarbon concentrations in the off-gas were measured. To quantify the extent of biodegradation at the site, the oxygen was converted to an equivalent basis. This was based on the stoichiometric oxygen requirement for hexane mineralization.[1] Hydrocarbon concentrations were determined based on direct readings of a total hydrocarbon analyzer calibrated to hexane. Based on these calculations, the mass of the JP-4 jet fuel as carbon removed (measured as amount of carbon removed) was approximately 1,500 lb volatilized and 93,000 lb biodegraded (Figure 4-1). After a 2-year period, cleanup and regulatory closure were achieved (Figure 4-2).

The results of this study indicated that aerobic biodegradation of JP-4 jet fuel did occur in the vadose zone at Site 914. Soil venting increased biodegradation at this site because, before venting, biodegradation appeared to have been oxygen limited. The SVE system, designed to volatilize the fuel, stimulated in situ biodegradation with no added nutrients or moisture. In this study, approximately 15 percent of the documented field removal observed at the site resulted from microbial-mediated mineralization to carbon dioxide. Additional biological fuel removal by conversion to biomass and degradation products no doubt occurred but was not quantified.

This study showed that further studies of field biodegradation in unsaturated soils were needed to better understand the effects of such variables as oxygen content, nutrient requirements, soil moisture, contaminant levels, and soil type on the limitation and optimization of bioventing of contaminated field sites. Also, further studies of gas transport in the vadose zone were needed to ensure adequate design of air delivery systems.

Further details of this study may be found in the following references: Dupont et al., 1991; Hinchee et al., 1991b.

4.2 Tyndall AFB, Florida

A more controlled study than was possible at Site 914, Hill AFB, was designed at Tyndall AFB as a follow-up to the Hill AFB research. The experimental area in the Tyndall AFB study was located at a site where past JP-4 jet fuel storage had resulted in contaminated soils. The

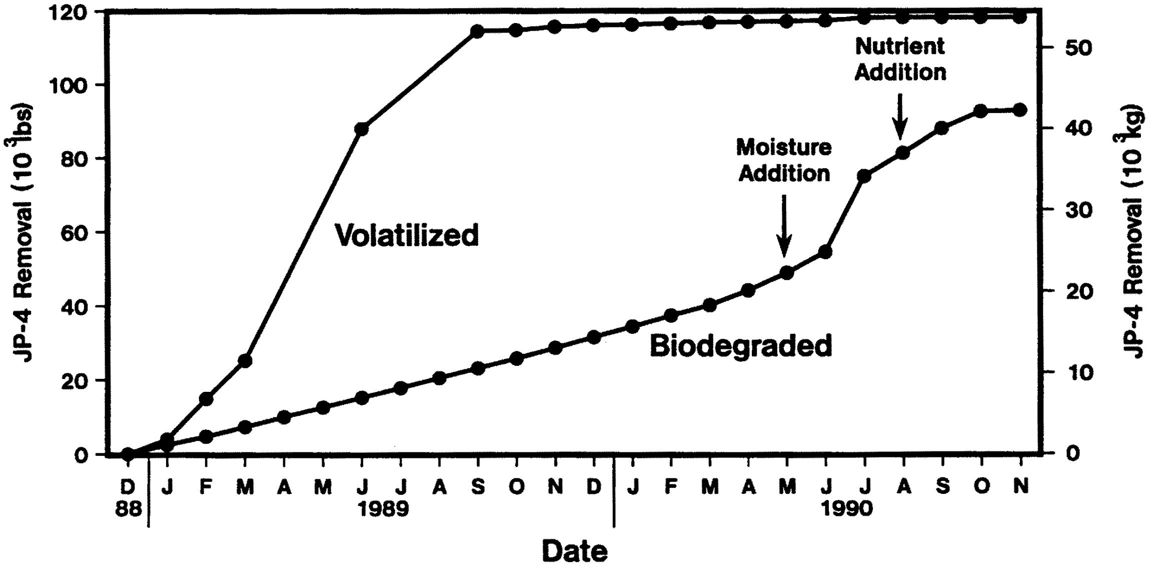


Figure 4-1. Cumulative hydrocarbon removal and the effect of moisture and nutrient addition at Site 914, Hill AFB, Utah.

---

[1] See Section 3.3 of Volume II for a discussion of this calculation.

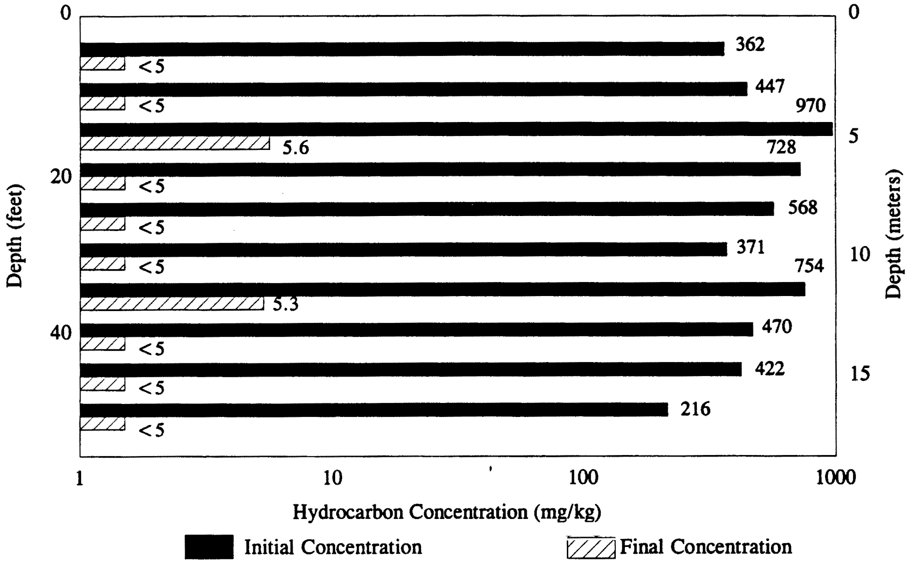


Figure 4-2. Results of soil analysis before and after treatment at Site 914, Hill AFB, Utah.

nature and volume of fuel spilled or leaked were unknown. The site soils were a fine- to medium-grained quartz sand. The depth to ground water was 2 ft to 4 ft (0.61 m to 1.2 m).

The field study was designed with the following objectives:

- To determine whether bioventing enhanced biodegradation of JP-4 jet fuel at this site.
- To determine whether moisture addition coupled with bioventing enhanced biodegradation rates.
- To determine whether nutrient addition coupled with bioventing enhanced biodegradation rates.
- To evaluate flow rate manipulation to maximize biodegradation and minimize volatilization.
- To calculate specific biodegradation rate constants from a series of respiration tests conducted during shutdown of the air extraction system.

Four test cells were constructed to allow control of gas flow, water flow, and nutrient addition. Test cells V1 and V2 were installed in the hydrocarbon-contaminated zone; test cells V3 and V4 were installed in uncontaminated soils. Test cells were constructed and operated in the following manner:

- *V1 (uncontaminated):* Venting for approximately 8 weeks, followed by moisture addition for approximately 14 weeks, then moisture and nutrient addition for approximately 7 weeks.
- *V2 (uncontaminated):* Venting coupled with moisture and nutrient addition for 29 weeks.
- *V3 (uncontaminated):* Venting with moisture and nutrient addition at rates similar to V2, with injection of hydrocarbon-contaminated off-gas from V1. Operation was conducted at a series of flow rates and retention times.
- *V4 (uncontaminated):* Venting with moisture and nutrient addition at rates similar to V2.

Initial site characterization indicated the mean soil hydrocarbon levels were 5,100 mg and 7,700 mg of hexane-equivalent/kg in treatment plots V1 and V2, respectively. The contaminated area was dewatered, and hydraulic control was maintained to keep the depth to water at approximately 5.25 ft (1.6 m). This exposed more of the contaminated soil to aeration. During normal operation, air flow rates were maintained at approximately one air-filled void volume per day.

Biodegradation and volatilization rates were much higher at the Tyndall AFB site than those observed at Hill AFB. These higher rates were likely the result of higher average levels of contamination, higher temperatures, and higher moisture content. Biodegradation rates during bioventing ranged from approximately 2 mg/kg-day to 20 mg/kg-day, with an average value of 5 mg/kg-day. After 200 days of aeration, an average hydrocarbon reduction of approximately 2,900 mg/kg was observed. This represented a reduction in total hydrocarbons of approximately 40 percent.

Another important observation of this study was the effect of temperature on the biodegradation rate. Miller (1990) found that the van't Hoff-Arrhenius equation provided an excellent model of temperature effects. In the Tyndall AFB study, soil temperature varied by only approximately 7°C (44.6°F), yet biodegradation rates were approximately twice as high at 25°C (77°F) than at 18°C (64.4°F).

Operational data and biodegradation rates indicated that soil moisture and nutrients were not limiting factors in hydrocarbon biodegradation for this site (Figure 4-3). The lack of moisture effect contrasts with the Hill AFB findings but most likely results from the contrasting climatic and hydrogeologic conditions. Hill AFB is located in a high-elevation desert with a deep water table. Tyndall AFB is located in a moist, subtropical environment, and at the study sites, the water table was maintained at a depth of approximately 5.25 ft (1.6 m). The nutrient findings support field observations made at Hill AFB that the addition of nutrients does not stimulate biodegradation. Based on acetylene reduction studies, Miller (1990) speculated that adequate nitrogen was present because of nitrogen fixation. The Hill and Tyndall AFB sites had been contaminated for several years before the bioventing studies began, and both sites were anaerobic. Nitrogen fixation, which is maximized under these conditions, may have provided the required nutrients. In any case, these findings show that nutrient addition is not always required.

The Tyndall AFB study included a careful evaluation of the relationship between air flow rates and biodegradation and volatilization. Researchers found that extracting air at the optimal rate for biodegradation resulted in 90 percent removal by biodegradation and 10 percent removal by volatilization. They also found that passing the contaminants volatilized in the off-gas through clean soil resulted in complete biodegradation of the volatilized vapors.

In situ respiration tests documented that oxygen consumption rates followed zero-order kinetics and that rates were linear down to 2 percent to 4 percent oxygen. Therefore, air flow rates can be minimized to maintain oxygen levels between 2 percent and 4 percent without fuel biodegradation, with the added benefit that lower air flow rates increase the percentage of removal by biodegradation and decrease the percentage of removal by volatilization.

The study was terminated because the process monitoring objectives had been met; biodegradation was still vigorous. Although the TPH had been reduced by only 40 percent by the time of study termination, the low-molecular-weight aromatics (the BTEX components) were reduced by more than 90 percent (Figure 3-18). Apparently, the bioventing process more rapidly removed BTEX compounds that other JP-4 fuel constituents.

Results from this study demonstrated the effectiveness of bioventing for remediating fuel-contaminated soils, the ineffectiveness of moisture or nutrient addition for increasing in situ biodegradation rates, and the importance of air flow rates for optimizing biodegradation over volatilization. This study demonstrated, however, that a long-term bioventing study was necessary to examine process variables. This led to the initiation of the Site 280, Hill AFB, and the Site 20, Eielson AFB, projects described in the following sections.

Further details of the Tyndall AFB study may be found in the following references: Hinchee et al., 1989; Miller, 1990; Miller et al., 1991.

4.3 Site 280, Hill AFB, Utah

A key objective of the study at Site 280 was to optimize the injection air flow rates. These efforts were intended to maximize biodegradation rates in JP-4 jet fuel-contaminated soils while minimizing or eliminating volatilization. The site studied was a JP-4 jet fuel spill at Hill AFB that had existed since the 1940s (Figure 4-4). The geology was similar to Site 914, while average

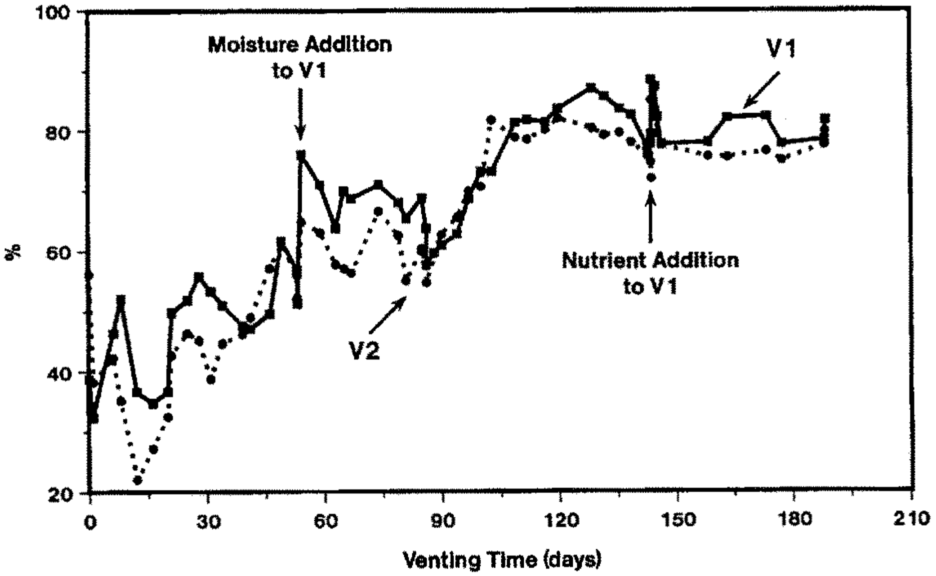


Figure 4-3. Cumulative percentage of hydrocarbon removal and the effect of moisture and nutrient addition at Tyndall AFB, Florida.

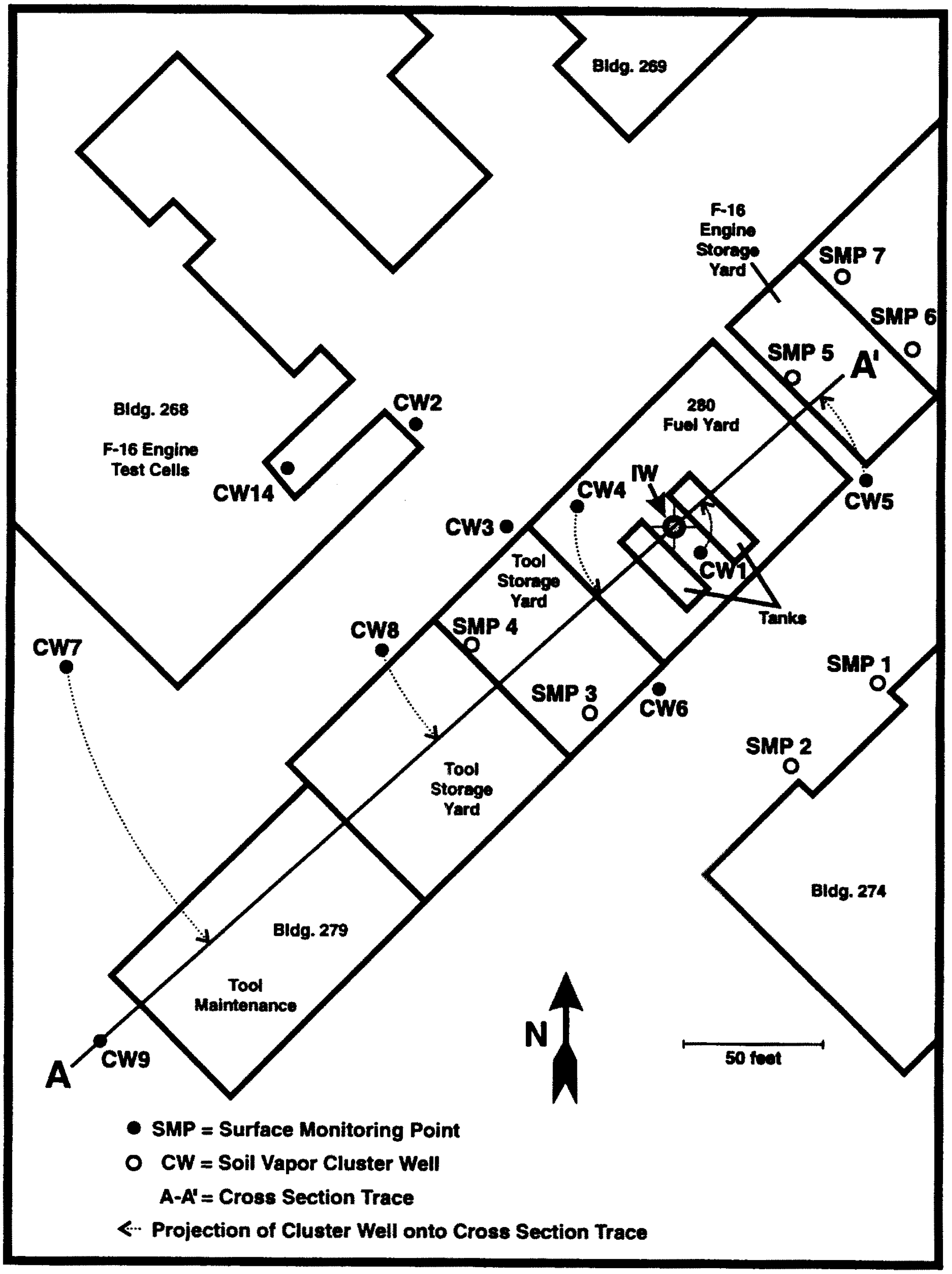


Figure 4-4. Schematic showing locations of soil gas monitoring points, surface monitoring points, and injection wells at Site 20, Hill AFB, Utah.

contaminant levels were slightly higher (Figure 4-5). Vent wells were installed to a depth of approximately 110 ft, and ground water was at a depth of approximately 100 ft.

From November 1992 through January 1995, many studies were conducted to evaluate low-intensity bioremediation at Site 280. These efforts included (1) varying the air injection flow rates in conjunction with in situ respiration tests and (2) testing surface emissions to obtain information for system optimization.

Five air flow rate evaluations were conducted at Site 280 from 1991 through 1994 (28, 67, 67, 40, and 117 cfm [790, 1,900, 1,900, 1,100, and 3,300 L/min]). In situ respiration testing followed each evaluation. The 67-cfm (1,900-L/min) study was repeated to include additional soil gas monitoring points added to the site. Monthly soil

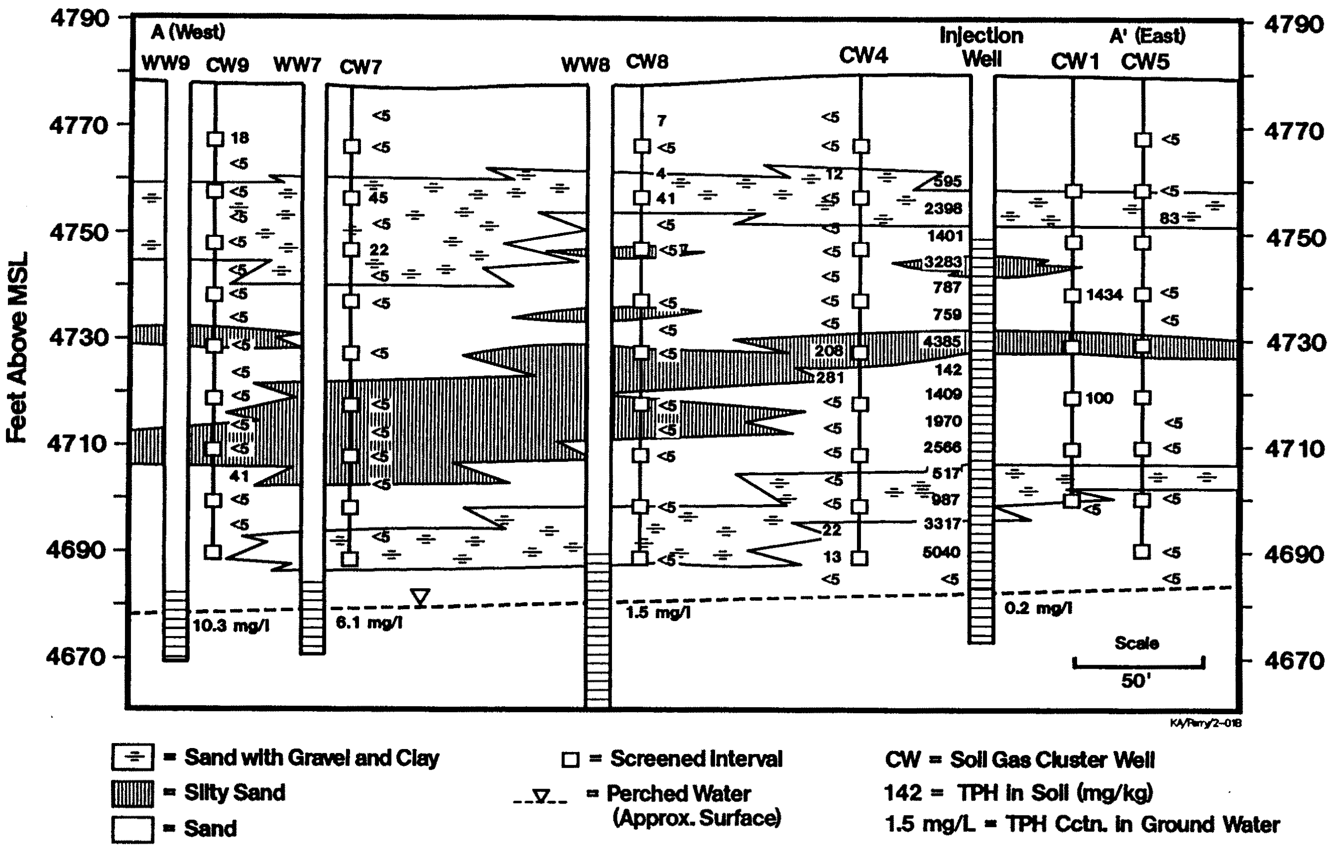


Figure 4-5. Geologic cross-section showing known geologic features and soil TPH concentrations (mg/kg) at Site 280, Hill AFB, Utah.

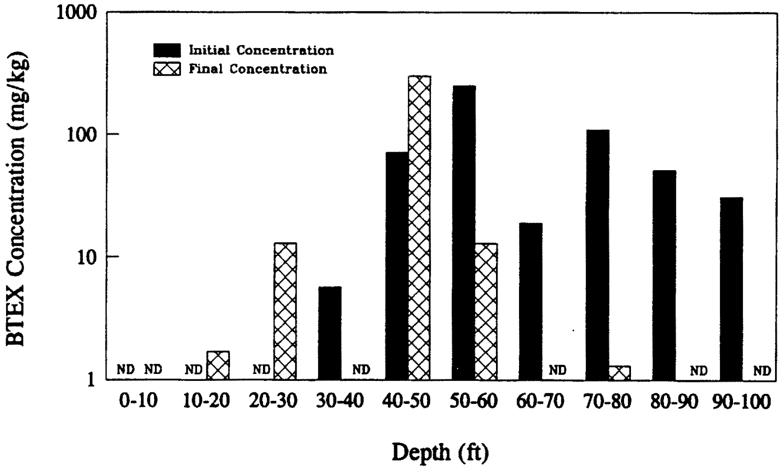
gas monitoring was conducted at Site 280 to measure the concentrations of oxygen, carbon dioxide, and TPH at each sampling point following system operation at each of the different air flow rates.

Surface emissions tests were conducted during each air injection test and while the air injection system was turned off. In each surface emissions test, no significant differences were found between the periods of air injection and no air injection. TPH soil gas levels measured during the air injection periods averaged approximately 70 ppmv, while TPH soil gas levels during resting periods averaged 42 ppmv. These averages were not found to be statistically different. Likewise, surface emission rates were not significantly different at different flow rates.

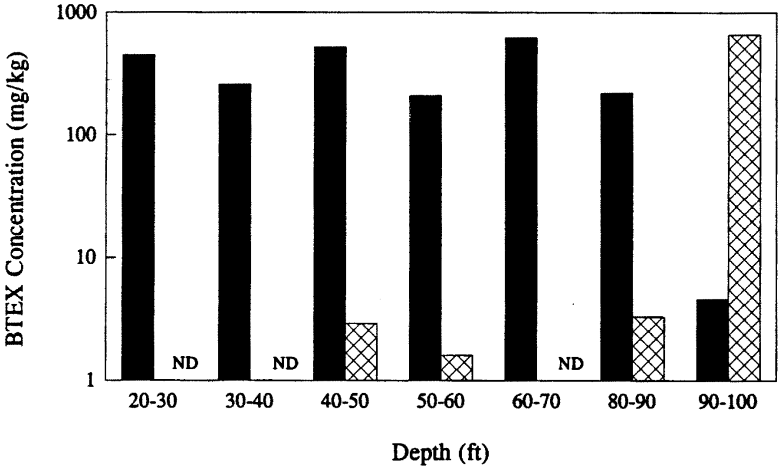
Final soil sampling was conducted in December 1994. Results of initial and final BTEX and TPH samples are shown in Figures 4-6 and 4-7, respectively. Results shown represent soil samples within a 0-ft to 25-ft radius of the injection well and a 25-ft to 75-ft radius. In general, BTEX and TPH concentrations decreased at all depths within the 25-ft radius from the vent well, with the exception of the samples collected at a depth of 90 ft to 100 ft. Samples taken from this depth are located at the capillary fringe, and adequate aeration probably was not possible. Samples collected outside of the 25-ft radius were less conclusive, indicating the lack of aeration in this area. Further details of the Site 280, Hill AFB, study may be found in the following reference: EPA, 1994b.

4.4 Site 20, Eielson AFB, Alaska

The objective of the Eielson AFB study was to install and operate an in situ soil bioremediation system to investigate the feasibility of using bioventing to remediate JP-4 jet fuel contamination in a subarctic environment and to actively increase soil temperature to determine the degree to which increased soil temperature can enhance the biodegradation rates of JP-4 contaminants in soil. This study comprised four test plots: (1) a test plot in which heated ground water was circulated through the test plot (active warming test plot), (2) a test plot in which plastic sheeting was placed over the ground surface of the test plot during the spring and summer months to capture solar heat and passively warm the soil (passive warming test plot), (3) a test plot in which heat tape was installed in the test plot to heat the soil directly (surface warming test plot), and (4) a control test plot, which received air injection but no soil warming (control test plot). In addition, an uncontaminated background location also received air injection but no soil warming to monitor natural background respiration rates. The site



a. BTEX Concentration Within a 25 to 75 ft Radius of the Injection Well



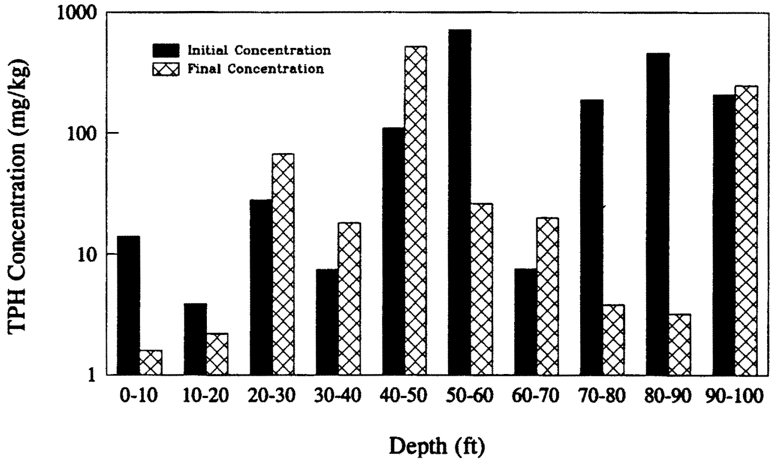
b. BTEX Concentration Within a 0 to 25 ft Radius of the Injection Well

Figure 4-6. Site average initial and final BTEX soil sample results at Site 280, Hill AFB, Utah.

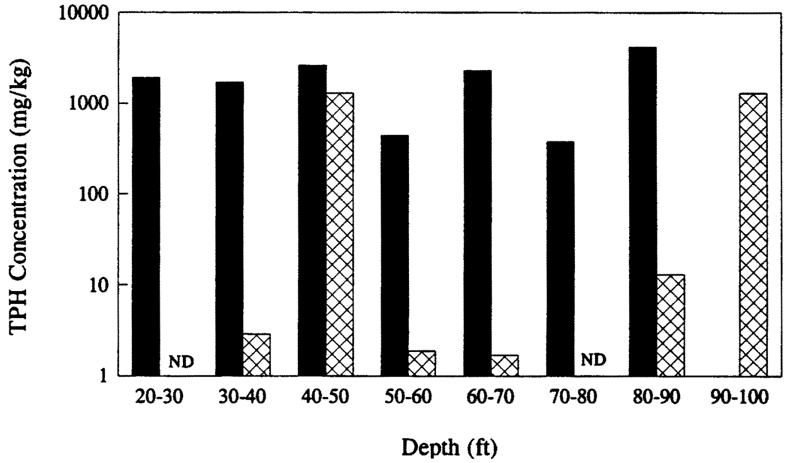
soils were a sandy silt, with increasing amounts of sand and gravel with depth. Ground water was typically at approximately 7 ft. Figure 4-8 illustrates site geologic features and typical construction details of the active warming test pilot, which is typical of other site installations as well.

Differences in soil temperatures have been significant among the four test plots (Figure 4-9). When in operation, the active warming test plot consistently maintained higher temperatures than the other test plots during the winter months. In the passive warming test plot, plastic sheeting increased soil temperature, with average soil temperatures as high as 18°C (64.4°F) during the summer months, compared with average temperatures of approximately 10°C (50°F) in the control test plot. A significant feature of this soil warming technique was that the addition of plastic sheeting in the spring caused a rapid increase in soil temperature, nearly 6 weeks to 8 weeks sooner than in unheated test plots. This significantly increased the period of rapid microbial degradation. During the winter months, the passive warming test plot remained warmer than the control test plot.

Respiration rates were measured quarterly in each test plot. Of particular interest were rates measured in the control test plot. No substantial microbial activity was expected to occur during the winter months in unheated test plots because of the extreme temperatures. Significant microbial activity was consistently measured in the control test plot, however, even in winter when soil temperatures are just below freezing (Figure 4-10). Respiration rates in the passive warming test plot were observed to increase nearly one order of magnitude as soil temperature increased during the summer months, indicating the success of using of plastic sheeting to promote soil warming (Figure 4-10). Respiration rates measured in the active warming test plot were higher than those measured in the passive warming or control test plot when warm water circulation was operating.



a. TPH Concentration Within a 25 to 75 ft Radius of the Injection Well



b. TPH Concentration Within a 0 to 25 ft Radius of the Injection Well

Figure 4-7. Site average initial and final TPH soil sample results at Site 280, Hill AFB, Utah.

Warm water circulation was discontinued in fall 1993, and as the soil temperature dropped, no significant microbial activity could be measured in the test plot during the winter months. This phenomenon is interesting in that it suggests that during the 2 years of soil heating, microorganisms adapted to growth at higher temperatures yet lost the ability to remain active in colder soils. To determine whether the microbial population could adapt to cold temperatures given time, a final in situ respiration test was conducted in January 1995. Significant microbial activity was measured, comparable to the control test plot, indicating either readaptation or recolonization by the microbial population.

The surface warming test plot has shown promise as a form of soil warming. Soil temperatures and respiration rates were higher than temperatures or rates in either the passive warming or control test plot and were similar to those measured in the active warming test plot during warm water circulation. These results indicate that the use of heat tape may prove to be a more efficient means of soil warming than hot water circulation because it avoids the problem of high soil moisture content.

An evaluation of cost versus remediation time was conducted to evaluate the feasibility of soil warming. Costs for the basic bioventing system in Table 4-1 were based on costs calculated by Downey et al. (1994). Given that average biodegradation rates were higher in the actively warmed plots, overall remediation time would be more rapid than in the unheated test plots (Table 4-1). Although capital costs were higher in the active and surface warming test plots, the rapid remediation time results in lower total cost for power and monitoring. Final costs based on dollars per cubic yard illustrate that costs are comparable among the four treatment cells. These results indicate that implementation of a soil warming technology over basic bioventing is not necessarily based on cost but on desired remediation time and funds available for operation and maintenance versus capital costs.

Final soil sampling at this site was conducted in August 1994. Results of initial and final BTEX and TPH samples

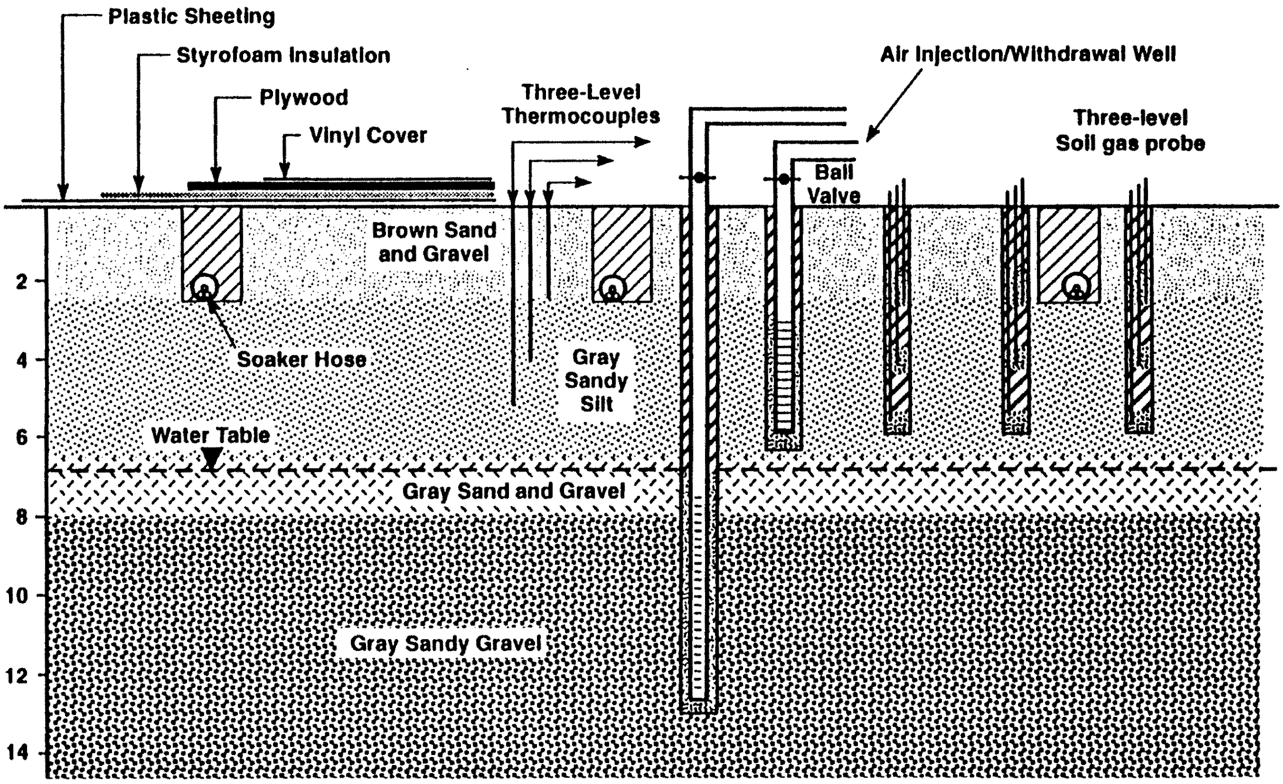


Figure 4-8. Cross-section showing geologic features and typical construction details of the active warming test plot, Site 20, Eielson AFB, Alaska.

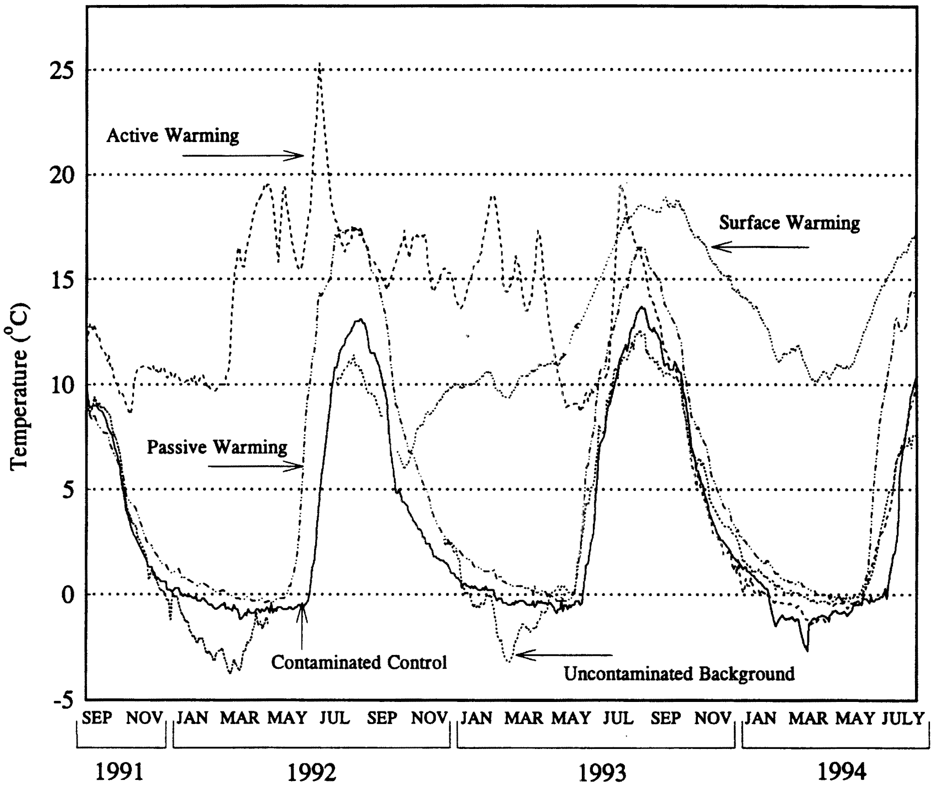


Figure 4-9. Soil temperature in four test plots and the background area at Site 20, Eielson AFB, Alaska.

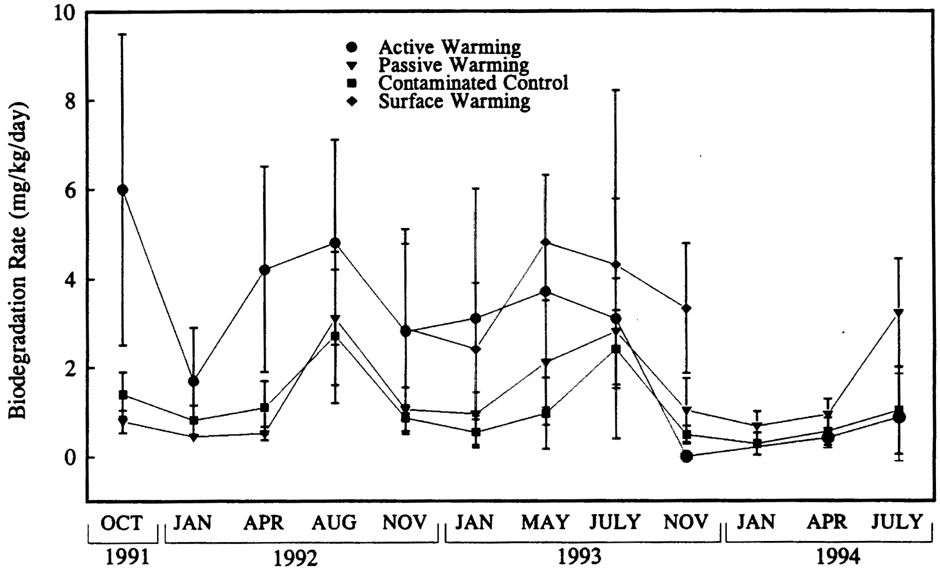


Figure 4-10. Biodegradation rates in four test plots at Site 20, Eielson AFB, Alaska.

Table 4-1. Cost Analysis of Soil Warming Techniques at Site 20, Eielson AFB, Alaska[a]

Task	Basic Bioventing (No Warming) ($)	Active Warming ($)	Passive Warming ($)	Surface Warming ($)
Site visit/planning	5,000	5,000	5,000	5,000
Work plan preparation	6,000	6,000	6,000	6,000
Pilot testing	27,000	27,000	27,000	27,000
Regulatory approval	3,000	6,000	3,000	3,000
Full-scale construction				
Design	7,500	7,500	7,500	7,500
Drilling/Sampling	15,000	20,000[b]	15,000	15,000
Installation/Startup	4,000	26,000	10,500	13,000
Remediation time required[c]	9.4 years	2.8 years	6.9 years	3.4 years
Monitoring	30,550	9,800	24,150	11,050
Power	13,160	9,800	9,660	17,000
Final soil sampling	13,500	13,500	13,500	13,500
Cost per yd[c]	25.50	26.12	24.86	24.21

[a] Costs are estimated based on a 5,000-yd^3 contaminated area with an initial contamination level of 4,000 mg/kg.
[b] Requires installation and development of one well.
[c] Estimated based on average biodegradation rates in four test plots.

are shown in Figures 4-11 and 4-12, respectively. A dramatic reduction in BTEX compounds was observed at all sample locations, while TPH was reduced by an average of approximately 60 percent.

Spatial variability in contaminant distribution and biodegradation rates makes quantitative comparison between the test plots difficult; however, the results from the active, surface, and passive warming test plots clearly demonstrate that these forms of soil warming have increased biological activity in these areas. In the active and surface warming test plot, despite problems caused by high oil moisture content, biodegradation rates consistently have been higher than those measured in either the passive warming or the control test plot, even though the control test plot appears to be more heavily contaminated than the active warming test plot. These results have demonstrated the feasibility of bioventing in a subarctic climate and the potential advantages of soil warming to decrease remediation times.

Further details of the Site 20, Eielson AFB study may be found in the following references: Leeson et al., 1995; EPA, 1994c.

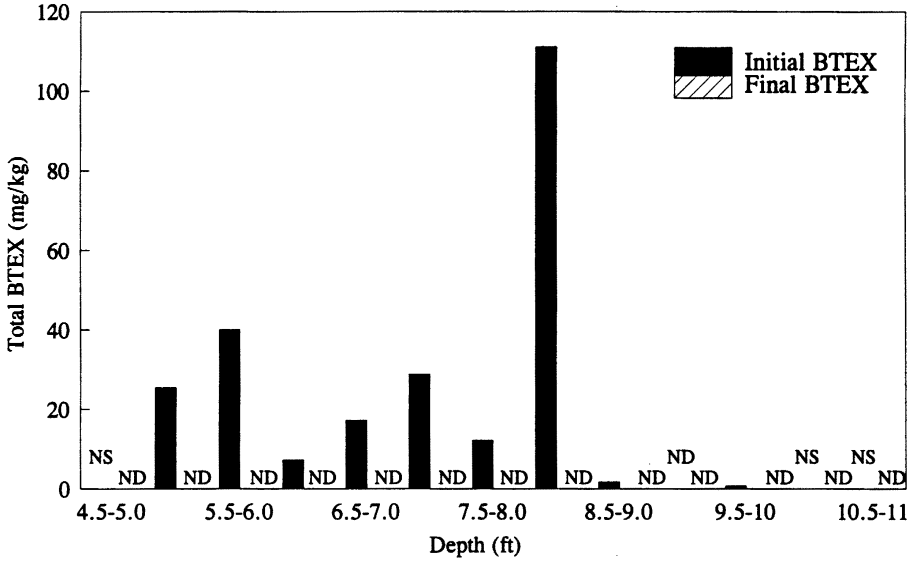


Figure 4-11. Site average initial and final BTEX soil sample results at Site 20, Eielson AFB, Alaska.

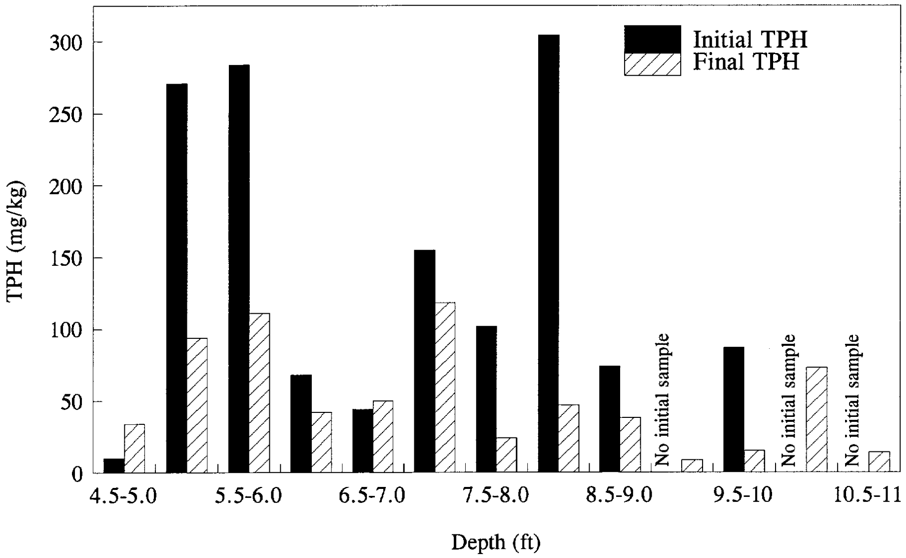


Figure 4-12. Site average initial and final TPH soil sample results at Site 20, Eielson AFB, Alaska.

4.5 Fire Training Area, Battle Creek ANGB, Michigan

The Fire Training Area, Battle Creek ANGB, was included as part of the Bioventing Initiative. An estimated 54,000 gal to 74,000 gal of mixed waste fuels, oils, and solvents were burned at this site during fire training exercises. Soils at the site consist of fine-to-coarse, silty sand interbedded with gravel and cobbles (Figure 4-13). Ground water is at a depth of approximately 30 ft.

As dictated by the Bioventing Initiative Protocol, one vent well and three monitoring points were installed at this site. The vent well was installed to a depth of 30 ft with 20 ft of 0.04-in. slotted screen. Each monitoring point consisted of three levels, with screens located at depths of 8 ft, 17 ft, and 27 ft. Monitoring points were located at distances of 15 ft, 30 ft, and 50 ft away from the vent well.

Initial treatability tests (an in situ respiration test and a soil gas permeability test) were conducted to determine the feasibility of bioventing. Oxygen utilization rates ranged from 2.9 to 22 percent/day (2.0 to 15 mg/kg-day), with higher rates associated with more contaminated locations. Soil gas permeability testing demonstrated an average permeability of approximately 230 darcy and a radius of

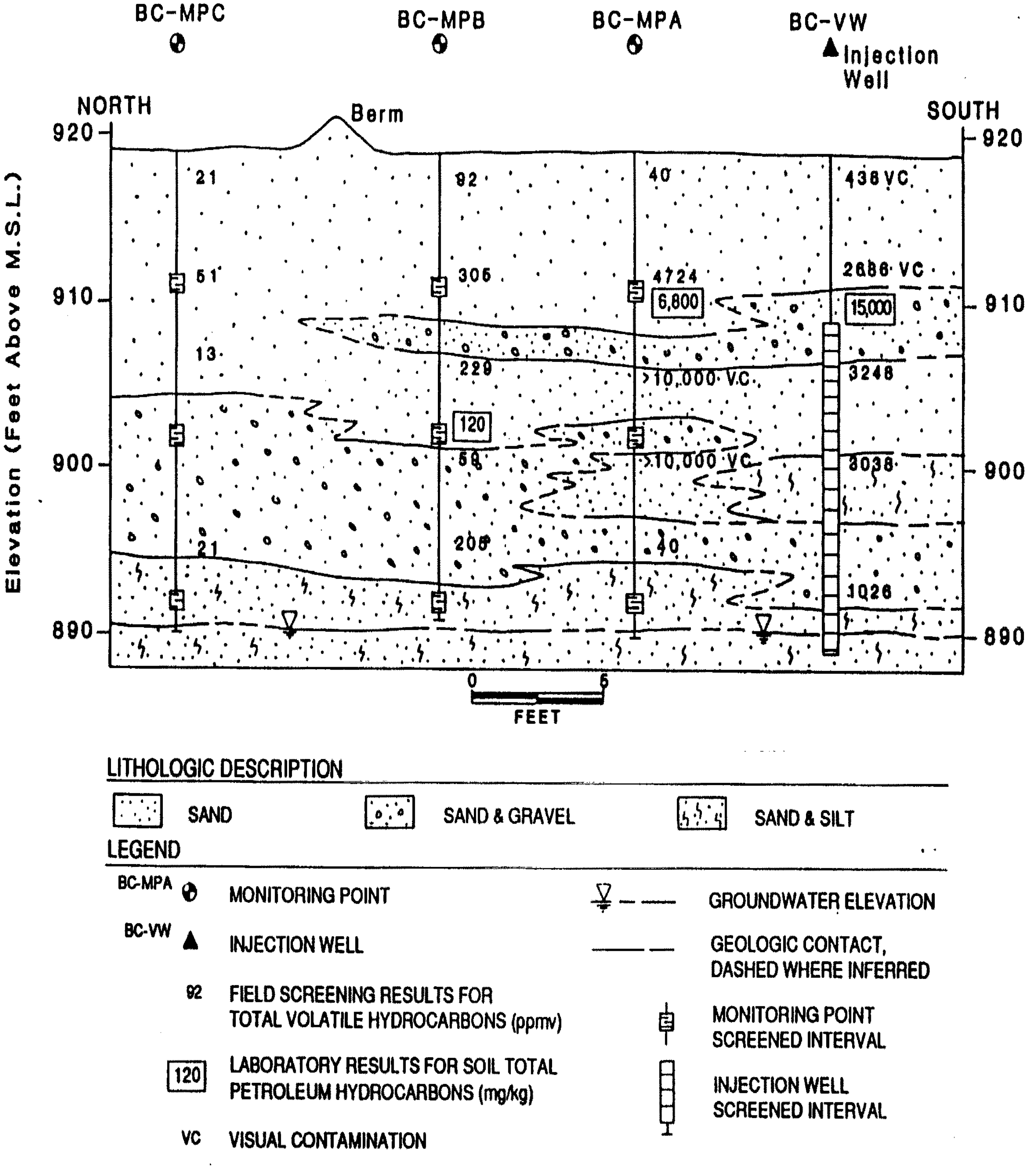


Figure 4-13 Hydrogeologic cross-section of the Fire Training Area, Battle Creek, ANGB, Michigan.

influence of greater than 50 ft. These results indicated that both the microbial activity and the permeability were conducive to an effective bioventing operation.

Initial soil and soil gas samples were collected, and a 1-hp regenerative blower was installed at the site for continuous air injection in September 1992. The blower was operated for 1 year, and in October 1993, final soil and soil gas samples were collected.[2] Although the number of soil[3] and soil gas samples collected was not sufficient to allow for statistically significant comparison

---

[2] Blower operation was discontinued for 1 month before collecting soil gas samples to allow time for soil gas equilibration.

[3] Three initial soil samples were collected, but 29 final soil samples were collected as part of an intrinsic remediation study.

of the data, certain trends were observed. Final BTEX and TPH soil gas concentrations were significantly lower than initial measurements (Figure 4-14). Soil BTEX concentrations were significantly lower after 1 year of bioventing, while soil TPH concentrations changed little, as expected (Figure 4-15). In addition, in situ respiration rates declined from the initial treatability test, which indicates decreased contaminant levels.[4] These results illustrated the effectiveness of bioventing at this site. Because Michigan uses a risk-based standard for site closure, this site is likely to be closed based on these results.

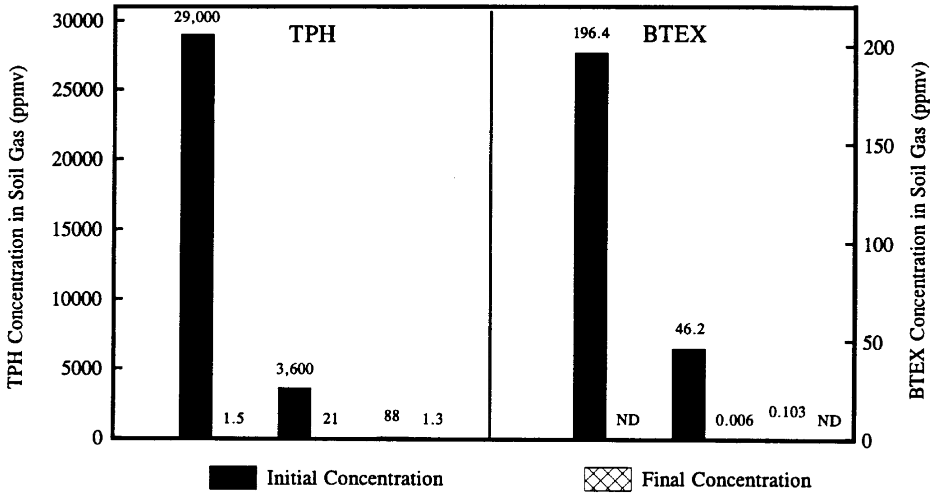


Figure 4-14. Initial and final soil gas concentrations at the Fire Training Area, Battle Creek, Michigan.

---

[4] See Chapter 4 of Volume II for a detailed discussion of in situ respiration rates and site closure.

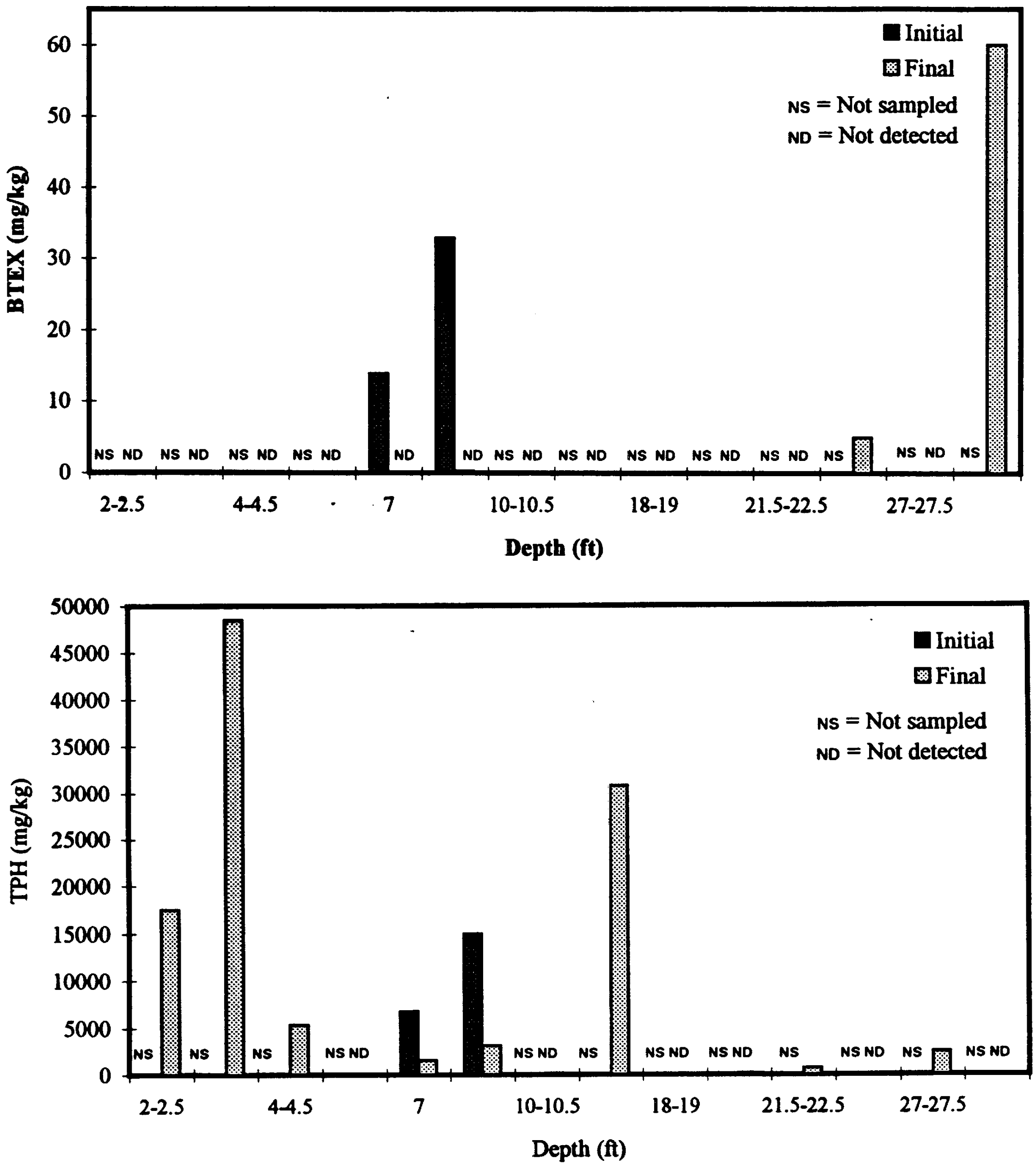


Figure 4-15. Initial and final soil concentrations at the Fire Training Area, Battle Creek, Michigan.

Chapter 5
Analyses of Bioventing Initiative Results

In May 1992, the U.S. Air Force began the Bioventing Initiative to examine bioventing at 55 contaminated sites throughout the country. In December 1992, the program was increased to more than 130 sites because of increased demand by Air Force managers. To date, data have been collected from 125 contaminated sites at a total of 50 Air Force bases, one Army base, one Naval installation, and one Department of Transportation installation. Sites are located in 35 states and in all 10 EPA regions. Figure 2-2 illustrates the locations of Bioventing Initiative sites to date. The selected sites represent a wide range of contaminant types and concentrations, soil types, contaminant depths, climatic conditions, and regulatory frameworks. Sites were selected based on contamination level (preferably greater than 1,000 mg/kg TPH). Selection was not biased regarding factors such as soil type or climatic conditions so that bioventing potential could be properly evaluated under favorable and unfavorable conditions.

A Bioventing Test Protocol was developed to provide strict guidelines for treatability testing and bioventing system design. The Bioventing Test Protocol was peer reviewed and was also reviewed by EPA Headquarters and the EPA National Risk Management Research Laboratory. Using the Bioventing Test Protocol, initial testing was conducted at each site to determine the feasibility of bioventing. Based on the initial testing, a decision was made about whether to install a bioventing system for 1 year of operation. At the majority of sites (95 percent), a bioventing system was installed for the 1-year operational period. At the end of this period, each Air Force base could either elect to keep the bioventing system in operation or remove it if the site was deemed to be sufficiently remediated.

At each site in which a bioventing system was installed, a series of data was collected as described in Section 2.3:

- Initial site characterization data consisting of soil and soil gas sampling, in situ respiration rate testing results, and soil gas permeability testing results.
- Six-month in situ respiration testing results.
- One-year soil and soil gas sampling and in situ respiration testing results. Data from the initial testing are summarized in Appendix B and have been used in the statistical analyses as described in Section 5.2. A summary of the results to date and potential implications are presented in the following sections.

5.1 Estimate of Contaminant Removal at Bioventing Initiative Sites

At all Bioventing Initiative sites in which a blower was installed and operated for 1 year, initial and final soil and soil gas BTEX and TPH concentrations have been measured. The approach was to compile a limited number of samples from each site and statistically analyze for trends to avoid known spatial variability. Distribution of soil and soil gas BTEX and TPH concentrations from the initial and 1-year sampling events are shown in Figures 5-1 through 5-4, respectively. The average soil and soil gas BTEX and TPH concentrations across all sites are shown in Figure 5-5. In general, the most dramatic reductions were observed in BTEX removal in both soil and soil gas samples. As an example, soil results from Site 3, Battle Creek ANGB, are shown in Figure 5-6. BTEX concentrations after 1 year of bioventing operation are very low and are no longer a source of ground water contamination; therefore, site closure is now a viable option for this site.

The objective of the 1-year sampling event was not to collect the large number of samples required for statistical significance for a single site. Rather, the sampling event was conducted to give a qualitative indication of changes in contaminant mass. Soil gas samples are somewhat similar to composite samples in that they are collected over a wide area. Thus, they indicate changes in soil gas profiles (Downey and Hall, 1994). Blower operation was discontinued 30 days before sample collection to allow for soil gas equilibration. In contrast, soil samples are discrete point samples subject to large variabilities over small distances/soil types. Given this variability, coupled with known sampling and analytical variabilities, many samples at a single site would have to be collected to conclusively determine real changes in soil contamination. Because of the limited number of samples, these results should not be viewed as conclusive indicators of bioventing progress or evidence of the success or failure of this technology.

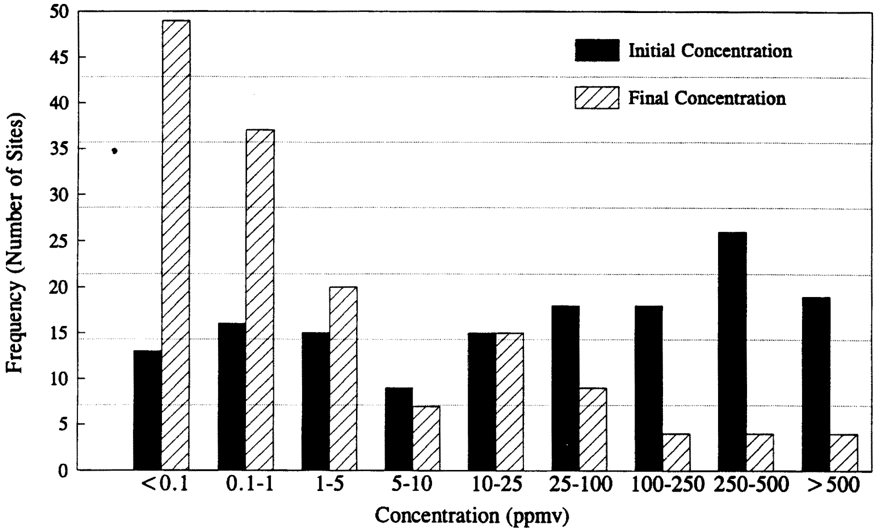


Figure 5-1. Soil gas BTEX concentrations at Bioventing Initiative sites: initial and 1-year data.

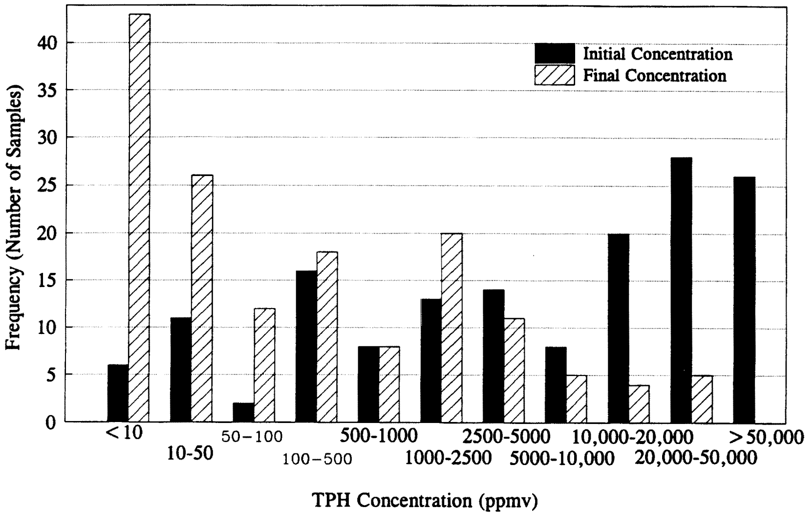


Figure 5-2. Soil gas TPH concentrations at Bioventing Initiative sites: initial and 1-year data.

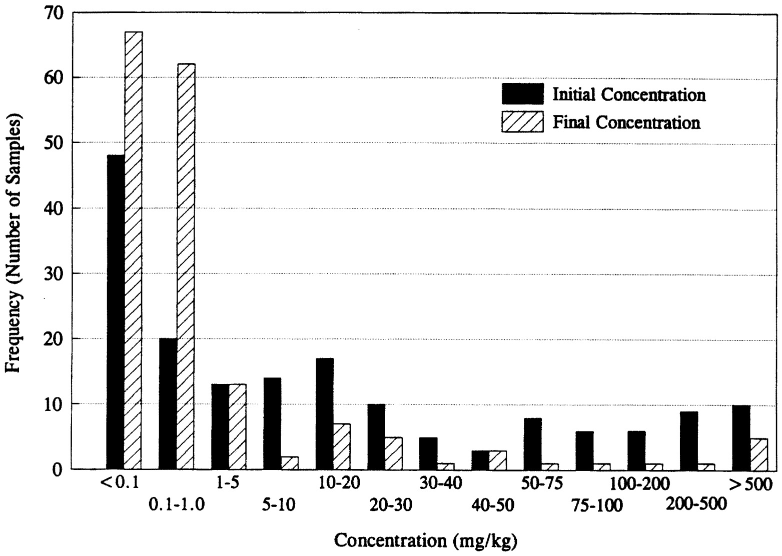


Figure 5-3. Soil BTEX concentrations at Bioventing Initiative sites: initial and 1-year data.

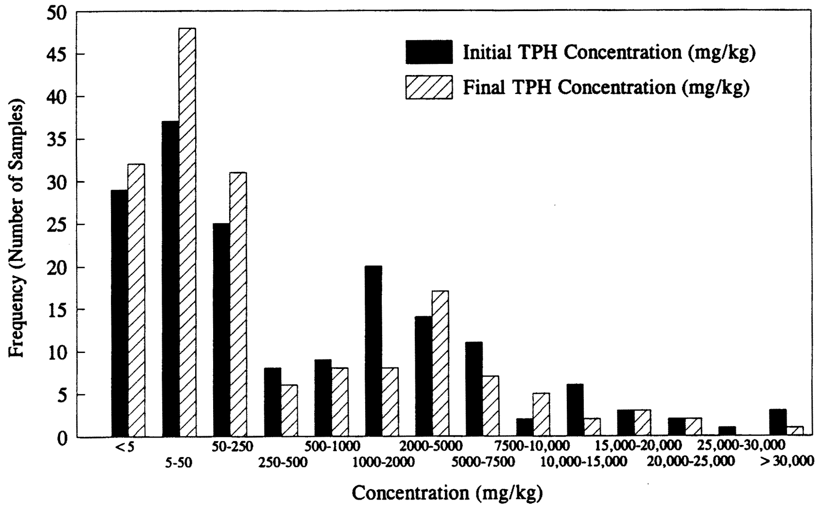


Figure 5-4. Soil TPH concentrations at Bioventing Initiative sites: initial and 1-year data.

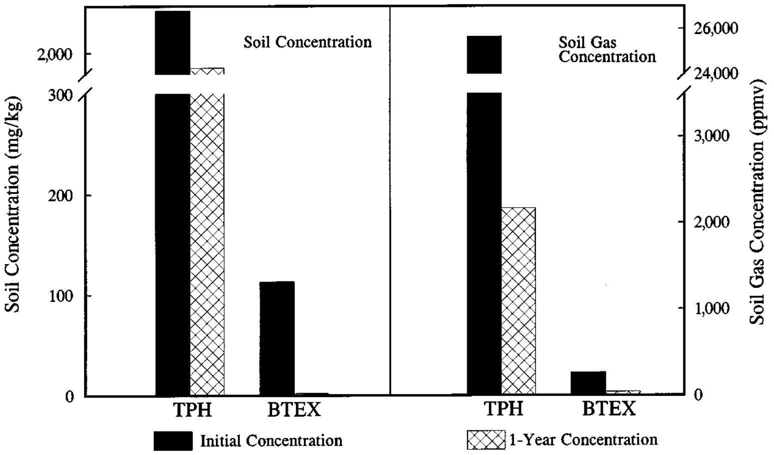


Figure 5-5. Average soil and soil gas BTEX and TPH concentrations at Bioventing Initiative sites: initial and 1-year data.

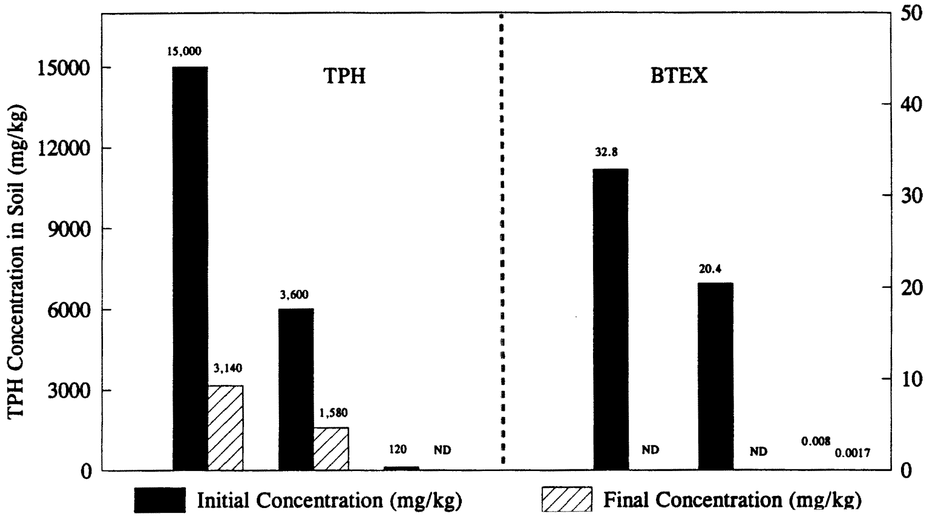


Figure 5-6. Initial and final soil sampling results at Site 3, Battle Creek ANGB, Michigan.

If a risk-based approach to remediation is used that focuses on removing the soluble, mobile, and more toxic BTEX component of the fuel, remediation times can be significantly reduced. As discussed in the Tyndall AFB case history,[1] the BTEX fraction was removed preferentially over TPH. The potential for bioventing to preferentially remove BTEX makes this technology suitable for risk-based remediations. In addition, the low levels of BTEX that have been encountered at the majority of Bioventing Initiative sites further supports an emphasis on risk-based remediation (Figure 5-7). Over 85 percent of the initial soil samples contained less than 1 mg/kg of benzene.

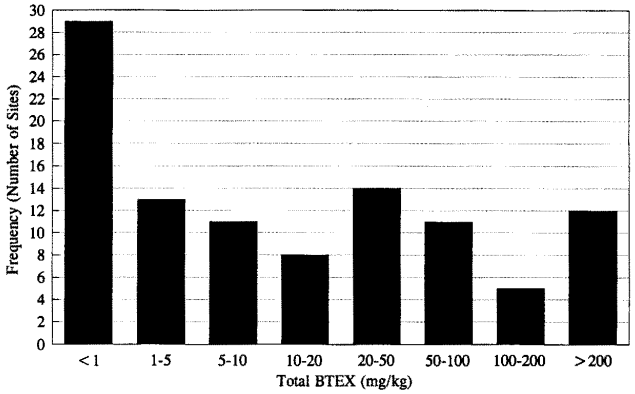


Figure 5-7. Average BTEX concentrations at Bioventing Initiative sites.

5.2 Statistical Analysis of Bioventing Initiative Data

One primary objective of the Bioventing Initiative was to develop a large database of bioventing systems that could be used to determine which parameters are most important in evaluating the feasibility of bioventing. This is the largest field effort to date where data have been collected in a consistent manner, allowing for direct comparison of results across sites. Results of the statistical analyses can be used to evaluate which soil measurements should be taken and, if bioventing performance is poor, which parameters can be adjusted to improve performance.

Data generated from the Bioventing Initiative were subjected to thorough statistical analyses to determine which parameters most influenced observed oxygen utilization rates. Procedures used for conducting the statistical analyses and the results of these analyses are presented in the following sections.

5.2.1 Procedures for Statistical Analysis

Data collected from 125 Bioventing Initiative sites have been analyzed for this study. The study involved in situ respiration test data, soil gas permeability test data, and soil chemistry and nutrient data from each site. Several parameters were measured in the soil samples. The statistical analyses had five specific objectives:

- To develop a consistent statistical approach for calculating the oxygen utilization and carbon dioxide production rates from the in situ respiration data.
- To characterize the oxygen utilization rate as a function of parameters measured during initial testing.
- To determine the relationship between carbon dioxide production rate and pH or alkalinity by characterizing the ratio of oxygen utilization rate to carbon dioxide production rate as a function primarily of pH and alkalinity.
- To characterize soil gas permeability as a function of particle size and moisture content.
- To compare primarily TKN concentrations at contaminated sites with those at uncontaminated background areas.

Averages for oxygen utilization and carbon dioxide production rates and soil parameters were computed for each site. All subsequent analyses were performed on the site averages. Table 5-1 displays the parameters included in the statistical analyses, their units, and transformations performed on these parameters wherever necessary.

Data were stored in Statistical Analysis System (SAS) databases, and all statistical manipulations and analyses were conducted using the SAS software. Methods used for characterizing the data and the final regression model are presented in the following sections for each of the listed objectives.

5.2.2 Calculation of Oxygen Utilization and Carbon Dioxide Production Rates

A statistical analysis was conducted to consistently calculate oxygen utilization and carbon dioxide production rates. A linear time-related change in oxygen and carbon dioxide levels that is characterized by a constant (or zero-order) rate is typical of most sites. In some sites, however, a two-piecewise linear change is observed. An initial rapid rate is observed followed by a leveling off. This change in rates generally occurs once oxygen becomes limiting, typically below 5 percent to 10 percent oxygen.

The two-piecewise regression model, with a slope change at time t_0, was fitted to the oxygen (and carbon dioxide) versus time data obtained at every monitoring point. The piecewise regression model is presented below:

$$R_i = \alpha + \beta t_i \qquad t_i \leq t_0 \qquad \text{(Eq. 5-1)}$$

---

[1] See Section 4.2 for a presentation of this case history.

Table 5-1. Data Parameters Included in the Statistical Analyses

Category	Parameter	Units	Transformation[a]	Acronymb
In Situ Respiration Rates	Oxygen utilization rate	%/hr	Log	O_2
	Carbon dioxide production rate	%/hr	None	CO_2
	Ratio of the carbon dioxide production rate to oxygen utilization rate	No units	Square root	Ratio
Soil Parameters	Soil gas TPH	ppmv	Log	tphsg
	Soil gas BTEX	ppmv	Log	btexsg
	Soil TPH	mg/kg	Log	tphs
	Soil BTEX	mg/kg	Log	btexs
	pH	No units	Log	PH
	Alkalinity	mg/kg as $CaCO_3$	Log	ALK
	Iron content	mg/kg	Log	IRN
	Nitrogen content	mg/kg	Log	NIT
	Phosphorus content	mg/kg	Log	PHO
	Moisture content	% weight	None	MOI
	Gravel	% weight	None	GRA
	Sand	% weight	None	SAN
	Silt	% weight	None	SIL
	Clay[c]	% weight	None and log	CLA
	Soil gas permeability	Darcy	Log	PRM
	Soil temperature	Celsius	None	TMP
Other	Season (time of year)	Day	None	Season

[a] Transformation was applied to the parameter for purposes of statistical analysis.
[b] Acronym is used for the parameter in this report.
[c] The correlations presented in Figures 5-9 through 5-14 and Figure 5-17 are based on untransformed clay.

$$R_i = (\alpha + \beta t_{0)} + (\beta + \delta)\,(t_i - t_0) \qquad t_i > t_0 \qquad \text{(Eq. 5-2)}$$

where i = number of observations at each monitoring point (1, 2,...), and where:

R_i = measured i^{th} oxygen or carbon dioxide level at time t_i (%)
α = oxygen or carbon dioxide level at initial time (%)
β = rate of change of oxygen or carbon dioxide level with time (%/hr)
δ = increase or decrease in the rate of change at time t_0 (%/hr)
t_0 = time at which the slope change occurs (hr)

The piecewise regression model was implemented using the nonlinear regression procedure (NLIN procedure) in the SAS software package.

The parameter δ in the above model measures the increase or decrease in the slope at time t_0. Therefore, the statistical significance of confirmed the suitability of a two-piecewise model fitted to the data. The rate of oxygen utilization (or carbon dioxide production) was estimated from the slope of the first linear piece, β, wherever δ was statistically significant at the 0.05 significance level. For example, Figure 5-8 presents the piecewise linear model fitted to oxygen data at a monitoring point at Site FSA-1, AFP 4, where β was estimated to be -1.1 percent/hr.

In cases where δ was not significant at the 0.05 level, a linear regression model of the following form was fitted to the data:

$$R_i = \alpha + \beta t_i \qquad \text{for all } t_i \qquad \text{(Eq. 5-3)}$$

where:

the rate of oxygen utilization (or carbon dioxide production) was determined from the slope of the straight line, β.

For cases in which six or fewer observations were available at a monitoring point, or where the oxygen levels exhibited virtually no change over a short initial period followed by a linear change, the piecewise analysis was not attempted. In such cases, a linear regression model, as described above, was fitted. In these cases, the suitability of the linear model was confirmed by inspection of the model fit to observed data.

5.2.3 Correlation of Oxygen Utilization Rates and Environmental Parameters

A preliminary analysis of the untransformed data was performed in which a regression model was fitted to the oxygen utilization rate using forward stepwise regression.

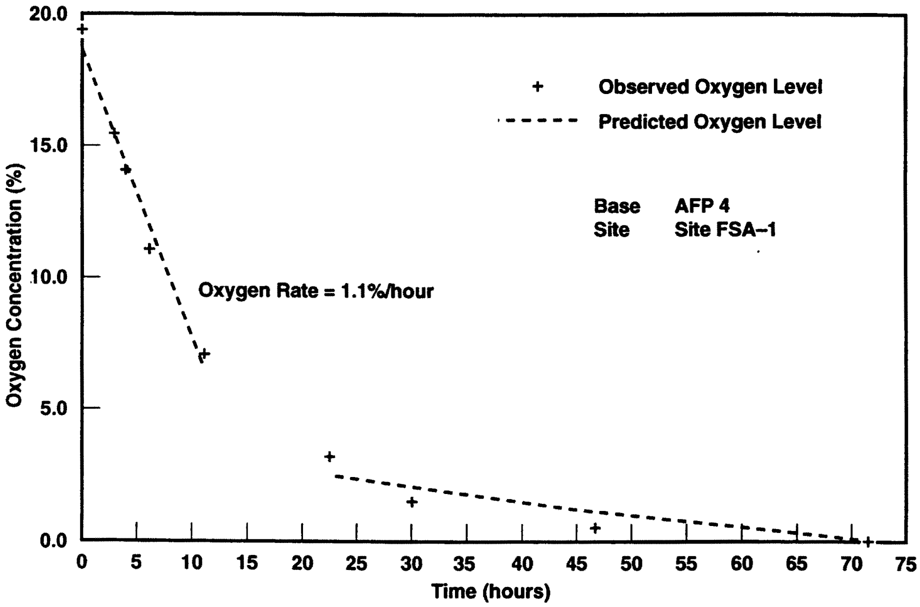


Figure 5-8. Use of piecewise analysis of oxygen utilization data from Site FSA-1, AFP 4, Texas.

This model accounted for the effects of the soil parameters and their interactions. To reduce the effect of multicollinearity among the parameters on the fitted model, soil gas BTEX levels and gravel were excluded from the modeling. In other words, soil gas BTEX was highly correlated with soil gas TPH, and therefore, it was concluded that the effect of soil gas BTEX levels on the oxygen utilization rate can almost completely be explained by soil gas TPH concentrations. Also, because the particle size levels added up to a constant value (100 percent), the effect of gravel was assumed to be redundant in the modeling.

Fitting the regression model to the oxygen utilization rate revealed that soil particle sizes and permeability had a dominating influence on the oxygen utilization rate; that is, low levels of permeability and sand, and high levels of silt and clay appeared to correlate strongly with high oxygen utilization rates.

To determine whether a handful of sites was unduly influencing the statistical modeling, sites with high oxygen utilization rates were examined in detail. Seven sites in the analyses had extremely high oxygen utilization rates, well above average rates from other sites. A two-sample t-test was performed on each parameter (e.g., sand, nitrogen) to determine whether the average value of the parameter over the seven sites was different from the corresponding average for the remaining sites. This analysis revealed statistically significant differences in particle size, soil gas permeability, and soil TPH concentrations between the two groups of sites (Table 5-2). The results of this analysis led to the determination that the seven sites with extremely high oxygen utilization rates were atypical with respect to their levels of particle size, soil gas permeability, and soil TPH concentrations.

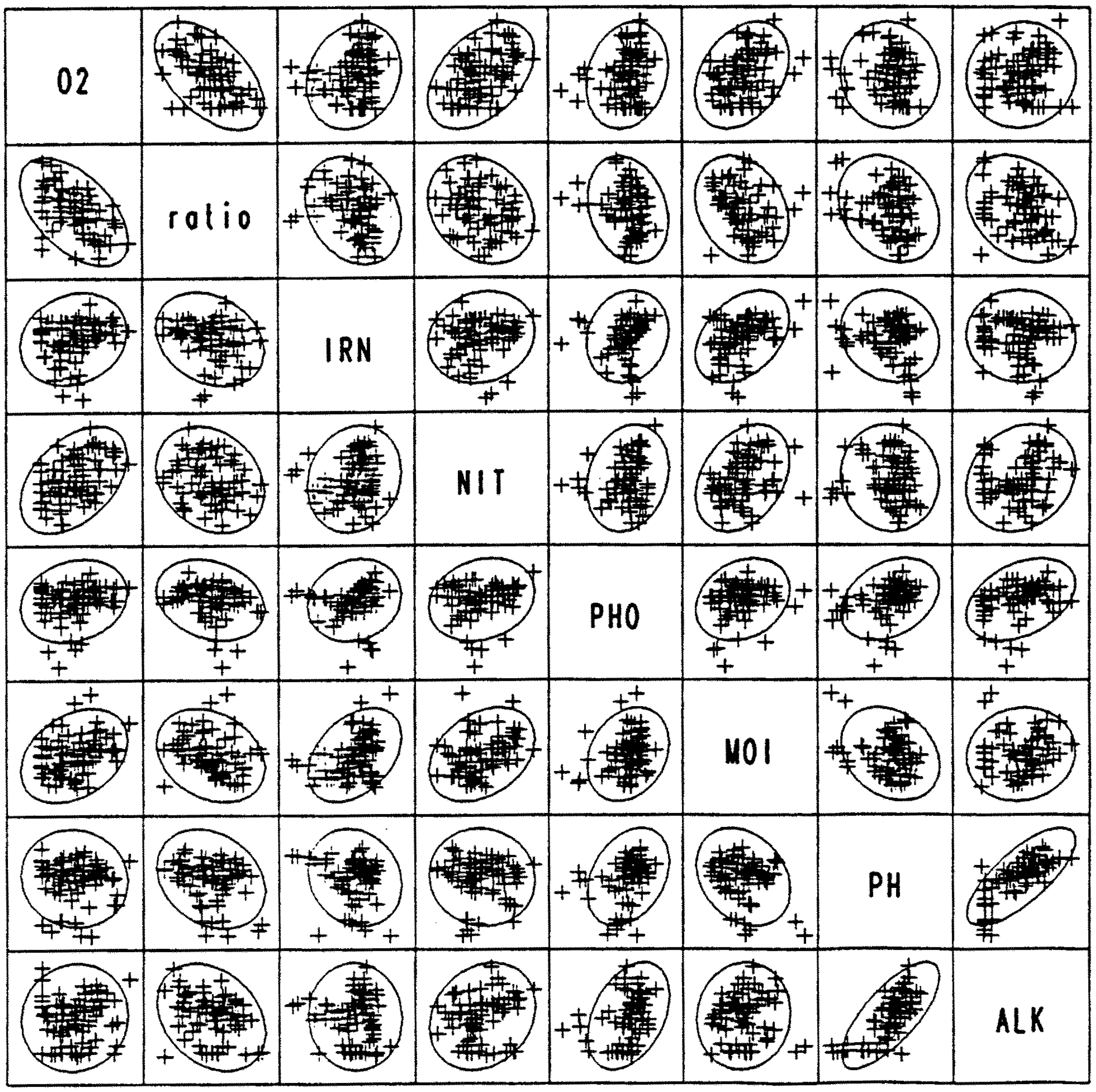
Table 5-2. Parameters That Distinguish the Seven Sites With High Oxygen Utilization Rates From the Remaining Sites

Parameter	Level of Parameter in Seven Sites Relative to Other Sites
Sand	Lower
Silt	Higher
Clay	Higher
Soil gas permeability	Lower
Soil TPH	Lower

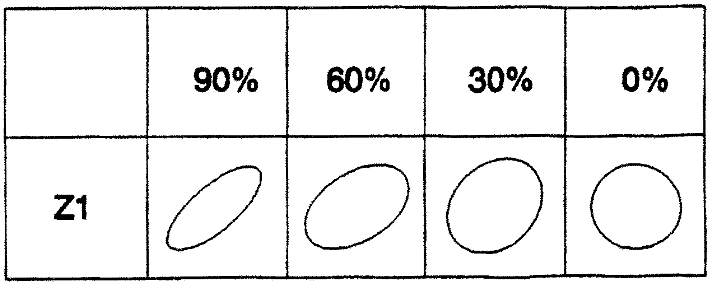
To reduce the influence of these seven sites on the model for oxygen utilization rate, the log transformation of the oxygen utilization rate was taken. Additionally, the log transform resulted in more normally distributed data for the oxygen utilization rate. Sites with oxygen utilization rates near zero, however, are artificially inflated in importance as a result of the transformation. To eliminate this artificial effect, all the log transformed values of the oxygen rate below -2.5 were censored (i.e., set to a constant value of -2.5). Censoring was based on visual inspection of the log transformed data.

Subsequently, the log transform of some soil parameters was taken if the data for the parameter were not well represented by a normal distribution. Normality in the data was checked using the Shapiro-Wilk test for normality and by observing histograms and normal probability plots.

As a preliminary step to determine the influence of soil parameters on oxygen utilization rate, correlations between each soil parameter and the oxygen utilization rate were examined. This was conducted to examine strong relationships between oxygen utilization rates

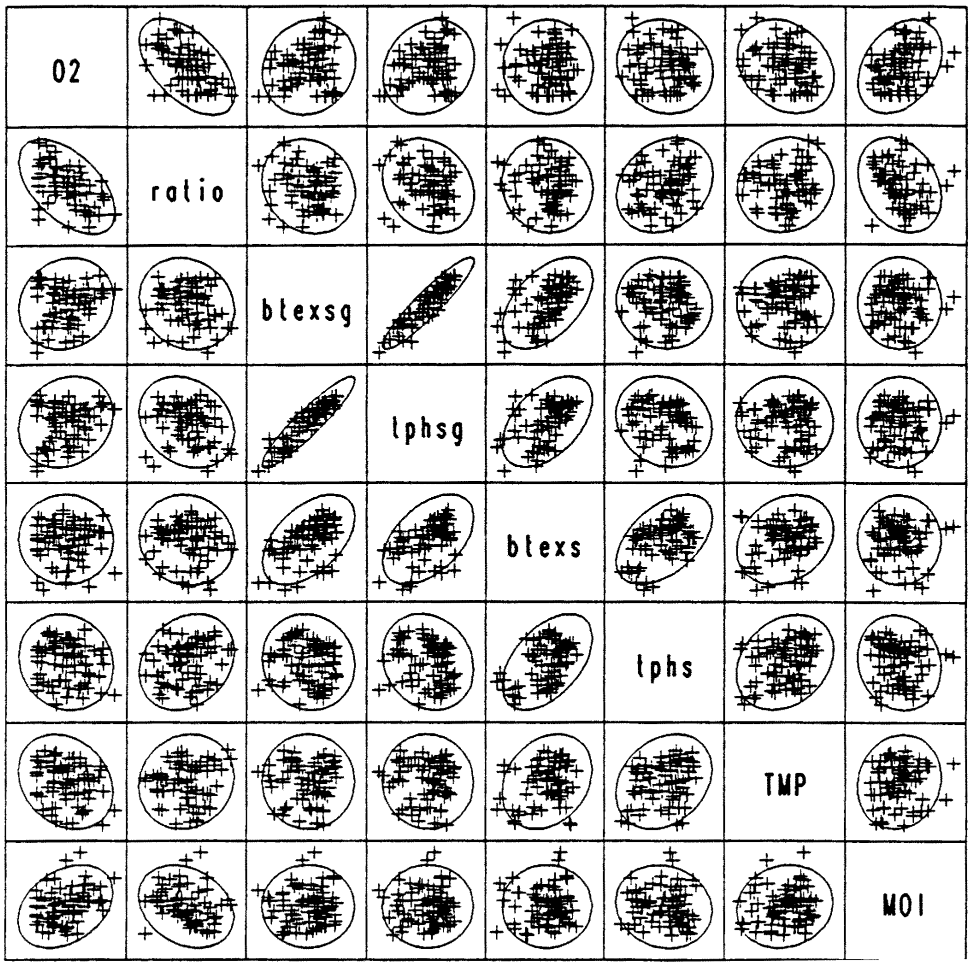


O_2 = log O_2 Rate   Ratio = $(CO_2 \text{ Rate}/O_2 \text{ Rate})^{1/2}$ IRN = log Iron   NIT = log Nitrogen
PHO = log Phosphorus   MOI = Moisture   PH = log pH   ALK = log Alkalinity

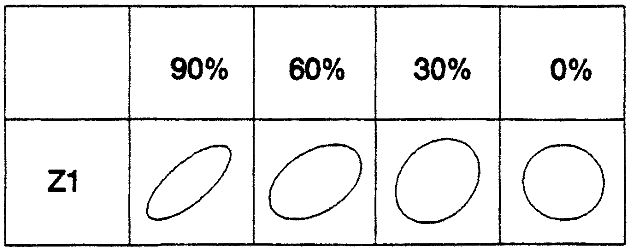


Key to Correlation Scatterplots.

Figure 5-9. Oxygen utilization rates, oxygen to carbon dioxide rate ratios, element concentrations, moisture content, pH, and alkalinity site average correlation scatterplot.

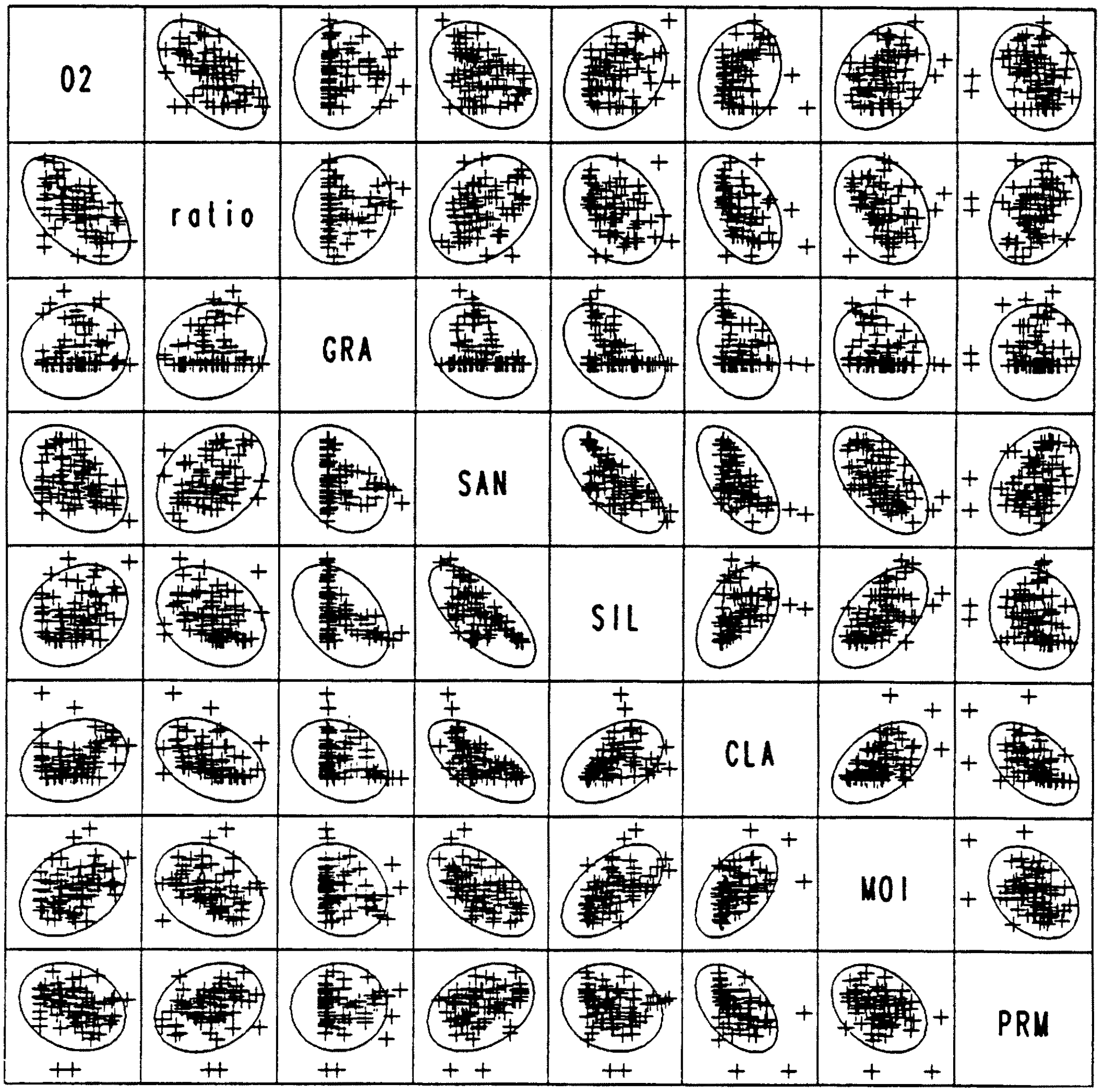


O_2 = log O_2 Rate   Ratio = (CO_2 Rate/O_2 Rate)$^{1/4}$ btexsg = log BTEX in Soil Gas   tphsg = log TPH in Soil Gas
btexs = log BTEX in Soil   tphs = log TPH in Soil   TMP = Soil Temperature   MOI = Moisture

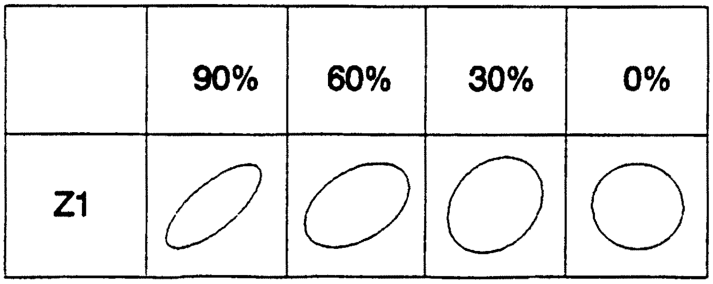


Key to Correlation Scatterplots.

Figure 5-10. Oxygen utilization rates, oxygen to carbon dioxide rate ratios, contaminant concentrations, temperature, and moisture content site average correlation scatterplot.

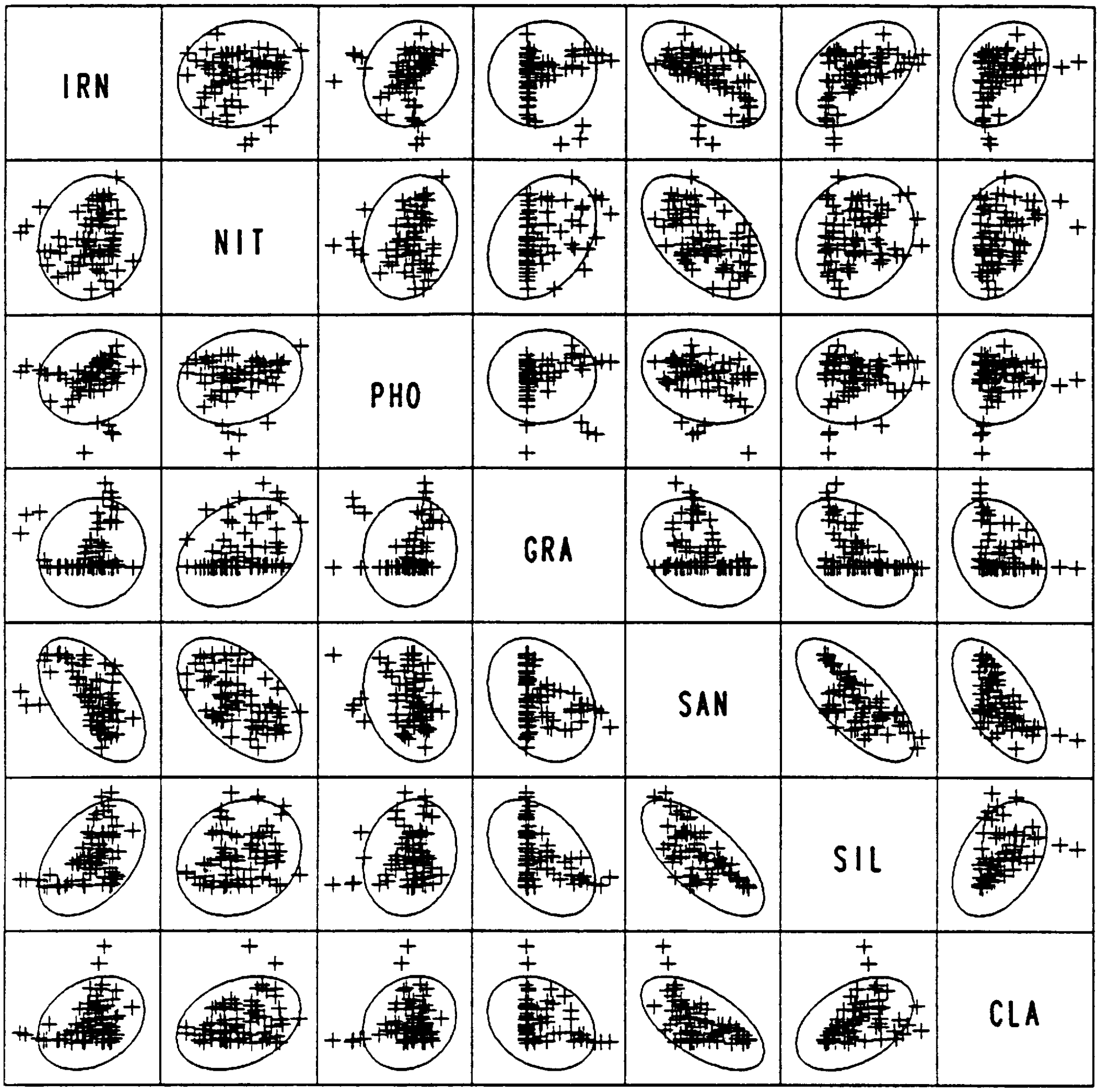


O_2 = log O_2 Rate Ratio = $(CO_2 \text{ Rate}/O_2 \text{ Rate})^{1/2}$ GRA = Gravel SAN = Sand SIL = Silt
CLA = Clay MOI = Moisture PRM = log Soil Gas Permeability

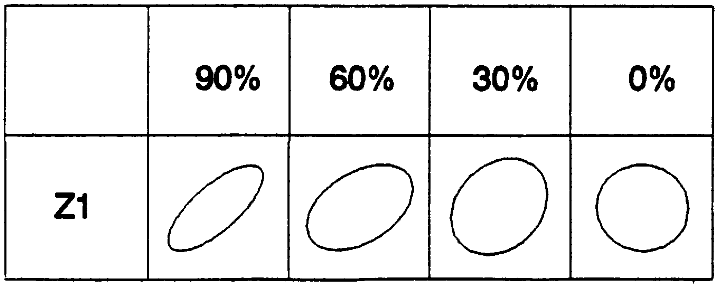


Key to Correlation Scatterplots.

Figure 5-11. Oxygen utilization rates, oxygen to carbon dioxide rate ratios, particle size, moisture content, and soil gas permeability site average correlation scatterplot.

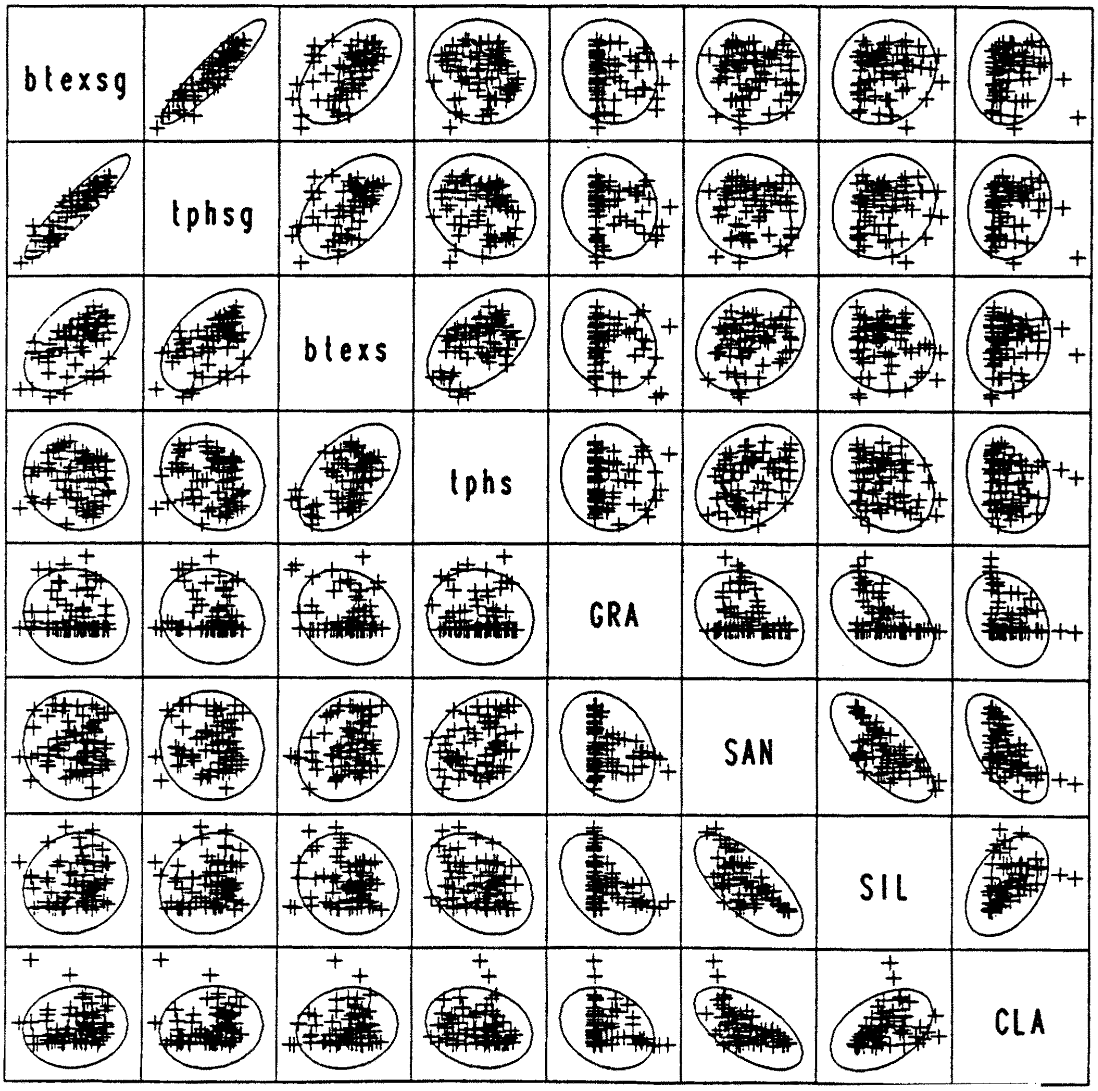


IRN = log Iron NIT = log Nitrogen PHO = log Phosphorus GRA = Gravel
SAN = Sand SIL = Silt CLA = Clay

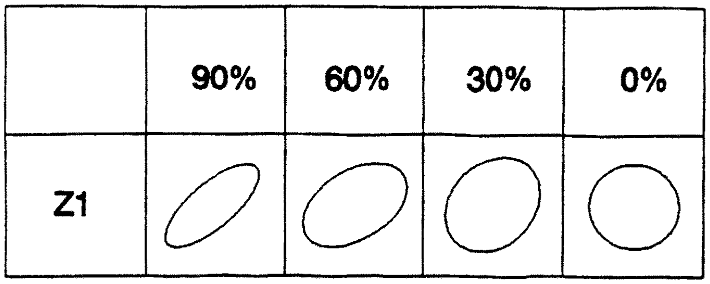


Key to Correlation Scatterplots.

Figure 5-12. Element concentrations and particle size site average correlation scatterplot.

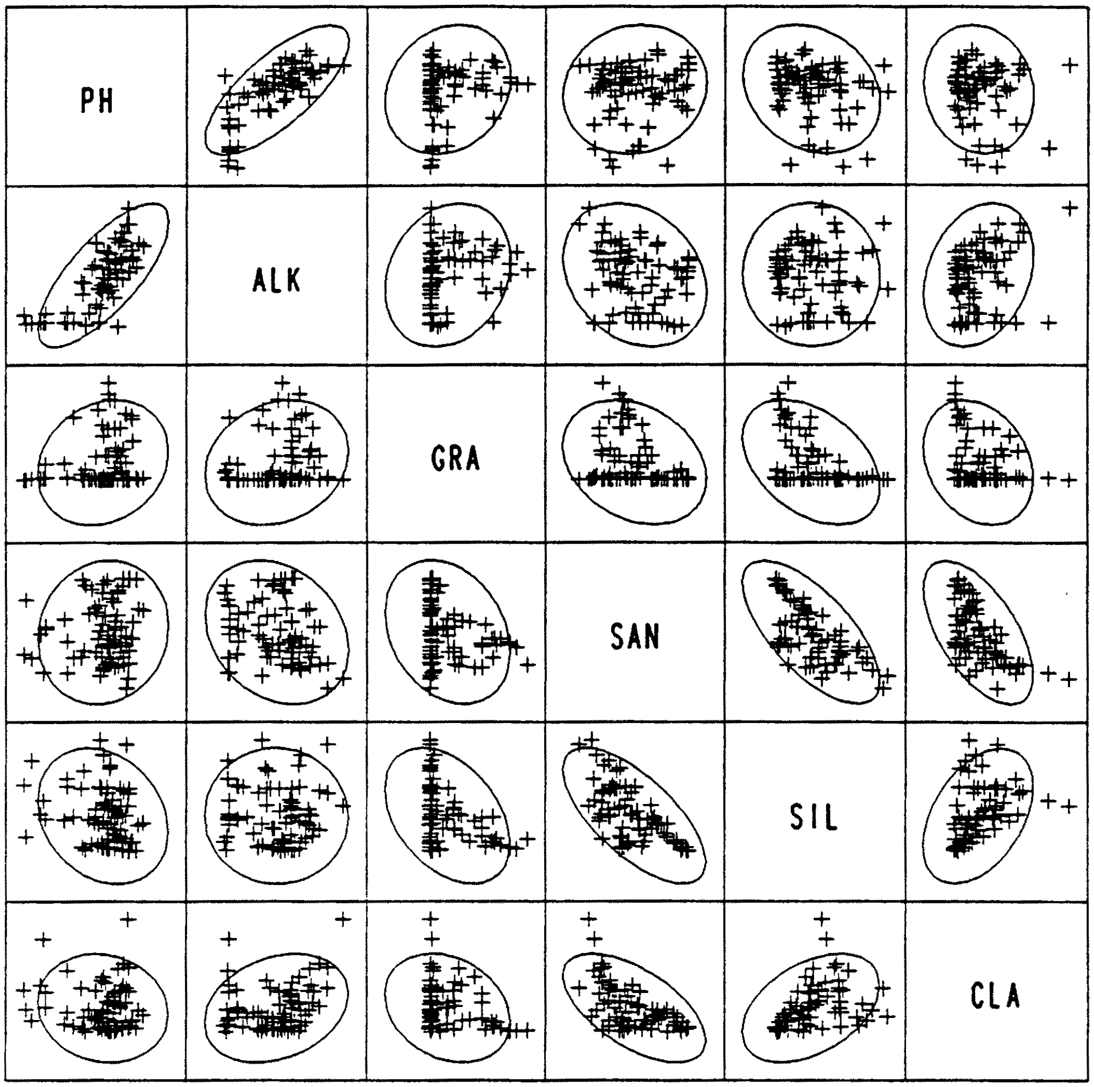


btexsg = log BTEX in Soil Gas tphsg = log TPH in Soil Gas btexs = log BTEX Soil
tphs = log TPH in Soil GRA = Gravel SAN = Sand SIL = Silt CLA = Clay

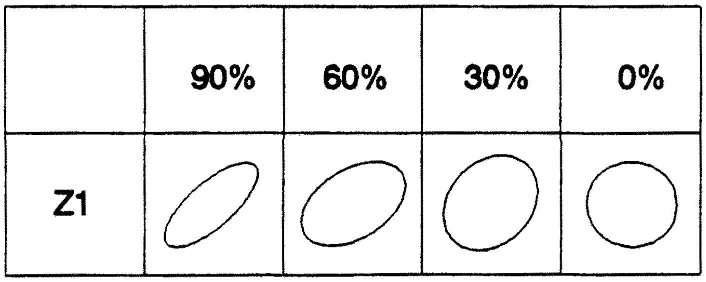


Key to Correlation Scatterplots.

Figure 5-13. Contaminant concentrations and particle size site average correlation scatterplot.



PH = log pH
ALK = log Alkalinity
GRA = Gravel
SAN = Sand
SIL = Silt
CLA = Clay



Key to Correlation Scatterplots.

Figure 5-14. pH, alkalinity, and particle size site average correlation scatterplot.

and measured environmental parameters to assist in developing a statistical model describing performance at the Bioventing Initiative sites. First, the log transformation of the oxygen utilization rate and some of the soil parameters was taken to obtain more normally distributed data on each parameter (Table 5-1). After these transformations, the data for each parameter were plotted against the corresponding data for each of the other parameters.

Figures 5-9 through 5-14 display the magnitude of the correlations among data parameters. Specifically, Figures 5-9 through 5-11 display the correlations between the oxygen utilization rate and the soil parameters, and Figures 5-12 through 5-14 present the correlations between soil parameters. In each figure, ellipses are drawn on each plot containing 95 percent of the estimated bivariate distribution. The plots with narrow ellipses represent pairs of elements that have a strong observed correlation. Pairs of elements that are positively correlated have the ellipse with the major axis running from the lower left to the upper right, while negative correlations are indicated by the major axis running from the lower right to the upper left. The magnitude of the correlation can be inferred from the shape of the ellipse by comparing it with the key figure. In the key figure, comparable ellipses are displayed for distributions with known correlations of 90 percent, 60 percent, 30 percent, and 0 percent.

For example, Figures 5-9 through 5-11 show that the oxygen rate is most positively correlated with nitrogen (Figure 5-9, correlation coefficient r = 0.40), moisture (Figure 5-9, r = 0.30), and soil gas TPH concentrations (Figure 5-10, r = 0.20) and negatively correlated with temperature (Figure 5-10, r = 0.25) and sand (Figure 5-11, r = 0.25). This indicates that high levels of nitrogen, moisture, and soil gas TPH concentrations, but low levels of sand and temperature, appear to correlate with high oxygen utilization rates.

The correlation between soil temperature and oxygen utilization rate is of little practical significance in this analysis, however. At a given site, temperature has been shown to correlate well with microbial activity, having peak activity in summer months and low activity in winter months. This relationship is also very site-specific, however. In other words, microorganisms in Alaska show peak activity in summer months with comparable oxygen utilization rates to those of organisms from more temperate climates; however, soil temperatures are significantly different. Therefore, correlating rates with temperature under such different climatic conditions as was seen at Bioventing Initiative sites is impossible.

Among the soil parameters, the correlation coefficient between soil gas BTEX and TPH concentrations is 0.92 (Figure 5-9) and that between pH and alkalinity is 0.75 (Figure 5-8). The correlations between the particle sizes (sand, silt, and clay), moisture, and soil gas permeability are also pronounced.

After taking the log transformation, a second regression model was fitted to the oxygen utilization rate using stepwise regression. Finally, the effect of a cyclic seasonal component on residuals obtained from the fitted regression model was investigated by including the date of the initial in situ respiration test.

The final regression model for oxygen utilization rate is:

$$\begin{aligned} \log(O_2) &= -2.7 + 0.39 \log(\mathrm{NIT}) - 0.108\,(\mathrm{MOI}) + \\ &0.017 \log(\mathrm{TPHsg}) * \mathrm{MOI} - \\ &0.004 \log(\mathrm{TPHsg}) * \mathrm{TMP} \qquad \text{(Eq. 5-4)} \end{aligned}$$

Each effect in the above model is statistically significant at the 0.05 significance level. Note that the effects appearing in the model are consistent with relationships observed in the bivariate setting. The model explains 41 percent of the variability in the log-transformed oxygen utilization rate (i.e., a 64-percent correlation between the observed and model-predicted log transformed oxygen rates). Figure 5-15 illustrates actual versus predicted oxygen utilization rates based on model predictions. As shown, the model appears to explain mid-range oxygen utilization rates fairly well but does not predict low oxygen utilization rates as accurately. This may be due to an effect on microbial activity that was not measured during the Bioventing Initiative and, therefore, was unexplained in the model.

5.2.4 Correlation of Oxygen Utilization and Carbon Dioxide Production Rate Ratios With Environmental Parameters

Because in situ biodegradation rates are measured indirectly through measurements of soil gas oxygen and carbon dioxide concentrations, abiotic processes that affect oxygen and carbon dioxide concentration will affect measured biodegradation rates. The factors that may most influence soil gas oxygen and carbon dioxide concentrations are soil pH, soil alkalinity, and iron content.

At nearly all sites included in the Bioventing Initiative, oxygen utilization has proven to be a more useful measure of biodegradation rates than carbon dioxide production. The biodegradation rate in mg of hexane-equivalent/kg of soil per day based on carbon dioxide production usually is less than can be accounted for by the oxygen disappearance. A study conducted at the Tyndall AFB site was an exception. That site had low-alkalinity soils and low-pH quartz sands, and carbon dioxide production actually resulted in a slightly higher estimate of biodegradation (Miller, 1990).

In the case of higher pH and higher alkalinity soils at such sites as Fallon NAS and Eielson AFB, little or no

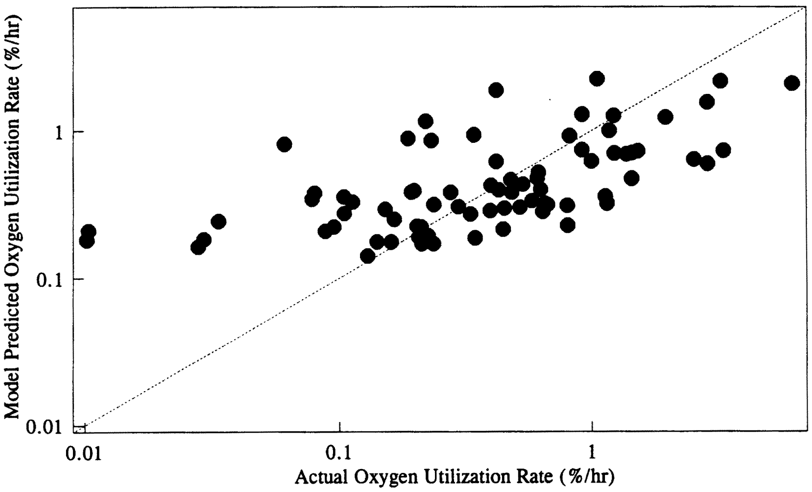


Figure 5-15. Actual versus model-predicted oxygen utilization rates.

gaseous carbon dioxide production was measured (Hinchee et al., 1989; Leeson et al., 1995). This may result from the formation of carbonates from the gaseous evolution of carbon dioxide produced by biodegradation at these sites. van Eyk and Vreeken (1988) encountered a similar phenomenon in their attempt to use carbon dioxide evolution to quantify biodegradation associated with soil venting.

To determine whether pH and alkalinity influenced carbon dioxide production rates at Bioventing Initiative sites, an analysis of the ratio of oxygen utilization to carbon dioxide production versus soil parameters was performed. Because of stoichiometry,[2] the ratio of the oxygen utilization to carbon dioxide production rate will not be 1 because for every 9.5 moles of oxygen consumed, 6 moles of carbon dioxide are produced. A square root transformation of the oxygen utilization and carbon dioxide production rate ratio (ratio) and log transformation of some of the soil parameters were taken wherever the data were not well represented by the normal distribution. Figures 5-9 through 5-11 display the bivariate relationships between the ratio and the soil parameters after the transformation. These figures, as expected, show a negative correlation between the ratio and the oxygen utilization rate (Figure 5-9, r = -0.45). The correlation of the ratio with clay is the most pronounced (Figure 5-11, r = -0.40). The ratio is also negatively correlated with pH (Figure 5-9, r = -0.25) and alkalinity (Figure 5-9, r = -0.30). As noted previously, pH and alkalinity are strongly positively related (Figure 5-9, r = 0.75). The correlations of the ratio with iron, moisture, permeability, and particle sizes are between 0.20 and 0.30 (Figures 5-9 and 5-11).

The statistical methods used to model the ratio of the oxygen utilization rate to carbon dioxide production rate as a function of the soil parameters are similar to those used for the oxygen utilization rate analysis. As a preliminary step, a square root transformation of the ratio and log transformation of some soil parameters were taken to obtain more normally distributed data. All transformations for the soil parameters except clay were consistent with those taken previously to model the oxygen utilization rate. A log transformation of clay was considered as it was more correlated with the ratio.

After applying the transformation, a regression model was fitted to the ratio using forward stepwise regression. The model accounted for the effects of all soil parameters (except season) and their interactions. Finally, the effect of a cyclic seasonal component on the residuals obtained from the fitted model was determined by incorporating the date of the initial in situ respiration test.

The final model for the ratio of the carbon dioxide production rate to the oxygen utilization rate is as follows:

$$\left(\frac{CO_2\ \text{rate}}{O_2\ \text{rate}}\right)^{\frac{1}{2}} = 1.28 - 0.38\log(\text{pH}) - 0.095\log(\text{clay}) + 0.0007\log(\text{tphs}) * \text{TMP} \qquad \text{(Eq. 5-5)}$$

Each effect in the above model is statistically significant at the 0.05 significance level. The model explains 40 percent of the variability in the transformed ratio. This amounts to a 63 percent correlation between the observed and model-predicted transformed ratios. The effects of pH on the ratio as predicted by the model are presented in Figure 5-16.

The complicated nature of the fitted regression model for the ratio makes the quantification of the effects in the model difficult. Figure 5-16, however, shows that as pH increases, the ratio of the carbon dioxide production rate to the oxygen utilization rate decreases, as would be expected given the formation of carbonates.

---

[2] See Section 3.2.1 for the stoichiometry of hydrocarbon degradation.

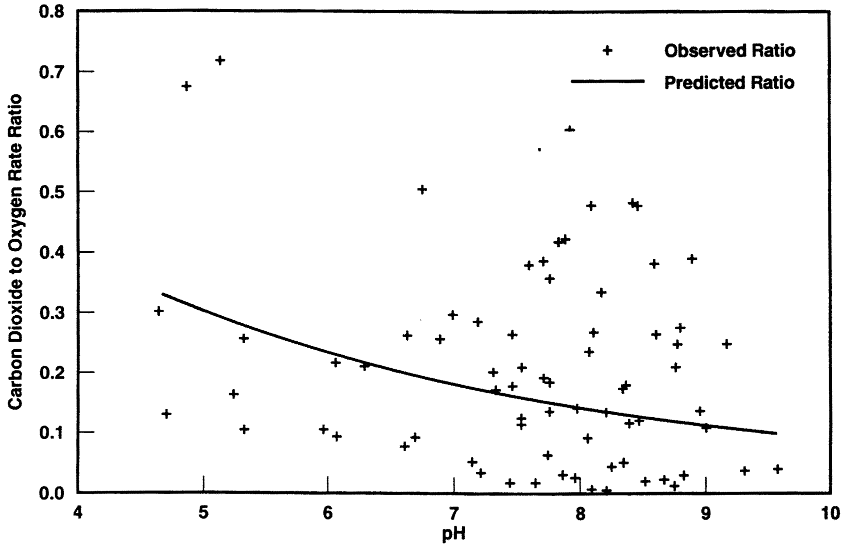


Figure 5-16. **Variation of pH and the effect on oxygen utilization to carbon dioxide rate ratio based on model predictions with average levels of other parameters.**

5.2.5 Correlation of Soil Gas Permeability With Environmental Parameters

The bivariate relationships between log-transformed soil gas permeability and each of the independent variables of interest are shown in Figure 5-17. In this figure, permeability correlates most strongly with clay (r = -0.50). The magnitude of the correlations with both moisture and sand are less pronounced and similar.

The statistical methods used here are similar to those described previously for the oxygen utilization rate and the ratio. Forward stepwise regression was used to determine a regression model for the log-transformed soil gas permeability. The independent variables of interest in the modeling were moisture content and particle size (sand, silt, and clay).

The final model describing soil gas permeability is given below:

$$\log(\mathrm{PRM}) = 3.2 - 0.064 \text{ clay} \qquad \text{(Eq. 5-6)}$$

Based on this model, clay alone explains 21 percent of the variability in the log-transformed soil gas permeability. The effect of clay on soil gas permeability as predicted by the model is presented in Figure 5-18. In this figure, the soil gas permeability levels greater than 100 have been censored (i.e., they were set to a constant value of 100). Based on the regression model it is determined that an increase in clay of 5 units decreases soil gas permeability by 25 percent on average.

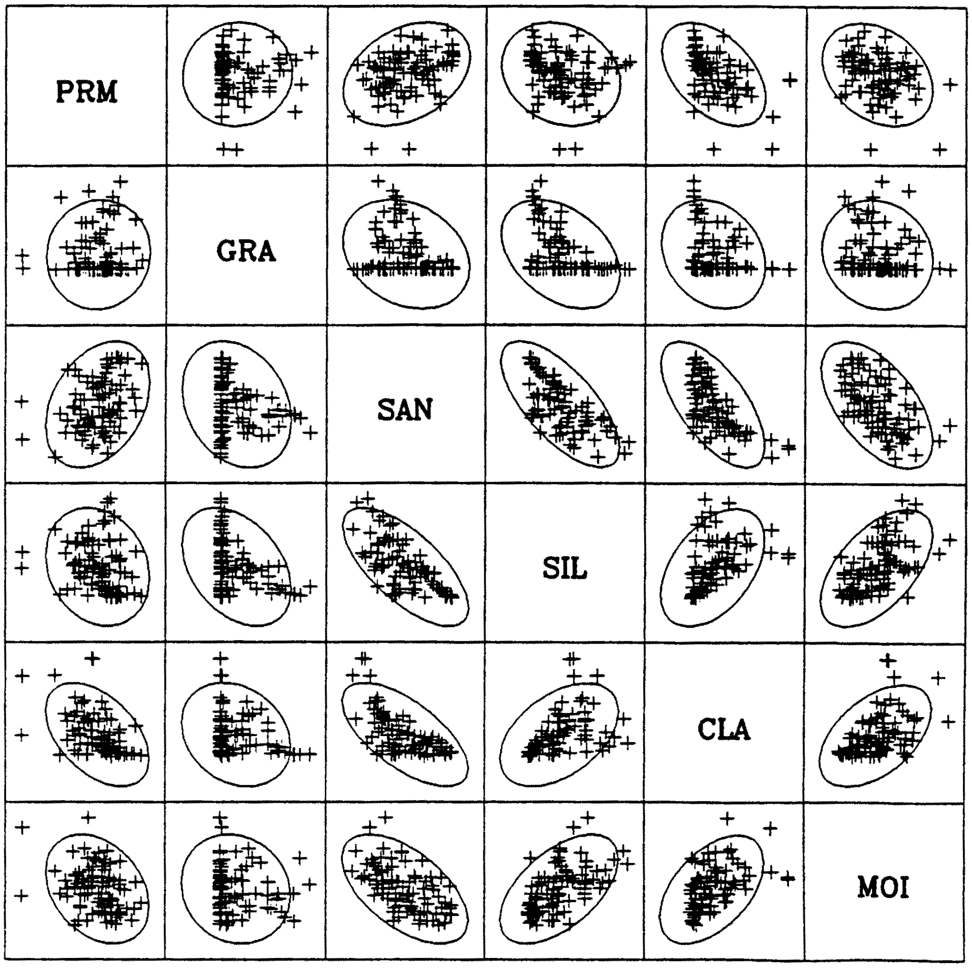
5.2.6 Analyses of Data From Contaminated and Background Areas

As the preliminary step to comparing the data at background and contaminated sites, transformations of the data parameters were considered. These transformations were consistent with those taken previously to address the other objectives of the statistical analysis. After taking the transformation, statistical analyses were performed separately on each parameter (e.g., nitrogen, oxygen rate). The goal of this analysis was to determine significant differences in the levels of each parameter at background and contaminated sites, with particular interest in TKN concentrations. Measurement of TKN accounts for nitrogen sources within cellular material; therefore, it is possible that TKN concentrations may be higher in contaminated areas, where microbial populations may be higher, than in uncontaminated areas. To date, no significant difference exists between TKN concentrations at contaminated sites (average of 232 mg/kg) and those at background areas (average of 226 mg/kg).

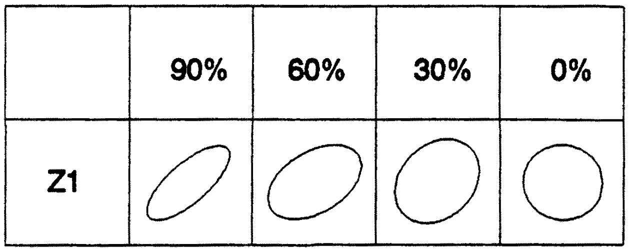
5.2.7 Summary

Based on the statistical analyses presented in the previous sections, the following overall conclusions are drawn:

- The relationships between biodegradation rates and soil parameters are not very strong. Some significant relative effects of the soil parameters stand out from the statistical evaluation conducted in the study, however. Namely, nitrogen, moisture, and soil gas TPH concentration appear to be the most important characteristics influencing observed field oxygen utilization rates.
- The ratio of the carbon dioxide production rate to the oxygen utilization rate correlates strongly with pH and clay levels in the soil.
- Soil gas permeability correlates with each particle size (sand, silt, and clay) and moisture content; however, the relative effect of clay on permeability is most important.



PRM = log Soil Gas Permeability GRA = Gravel SAN = Sand SIL = Silt CLA = Clay MOI = Moisture



Key to Correlation Scatterplots.

Figure 5-17. Soil gas permeability, moisture content, and particle size site average correlation scatterplot.

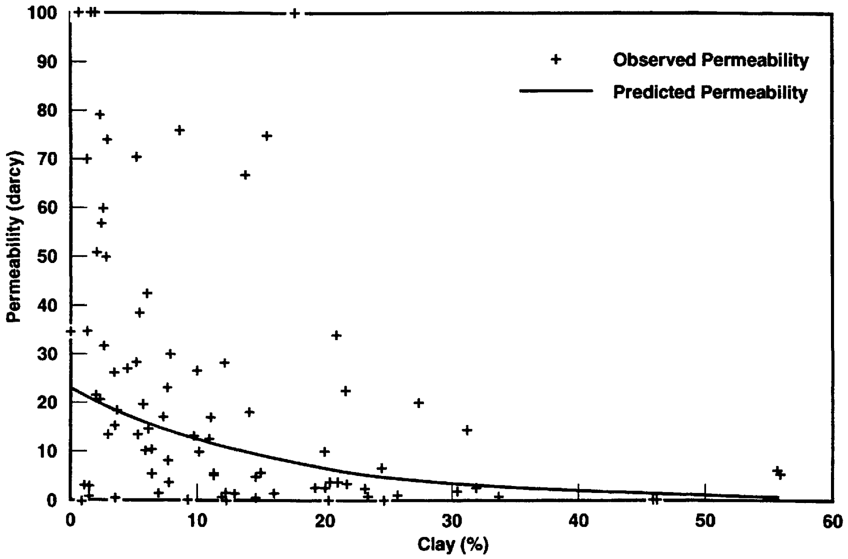


Figure 5-18. Variation of clay and the effect on soil gas permeability based on model predictions.

The Bioventing Initiative has provided a large database of information useful in the design and implementation of bioventing systems. The statistical analyses provide guidelines for determining which parameters are most important to bioventing technology. These data must be balanced, however, by experience and site-specific data. For example, sites with relatively low soil nitrogen concentrations should not be discarded as bioventing sites for this reason alone, nor should an assumption be made that nitrogen addition at these sites will increase oxygen utilization rates. Data collected from the U.S. Air Force Bioventing Initiative have shown that even sites with low soil nutrient concentrations can exhibit significant microbial activity and would therefore respond well to bioventing.

Chapter 6
References

Aggarwal, P.K., J.L. Means, and R.E. Hinchee. 1991. Formulation of nutrient solutions for in situ bioremediation. In: Hinchee, R.E., and R.F. Olfenbuttel, eds. In situ bioreclamation: Applications and investigations for hydrocarbon and contaminated site remediation. Stoneham, MA: Butterworth-Heinemann Publishing Company. pp. 51-66.

Alleman, B.C., R.E. Hinchee, R.C. Brenner, and P.T. McCauley. 1995. Bioventing PAH contamination at the Reilly Tar Site. In: Hinchee, R.E., and R.F. Olfenbuttel, eds. In situ aeration, air sparging, bioventing, and related remediation processes. Columbus, OH: Batelle Press. pp. 473-482.

American Petroleum Institute. 1987. Field study of enhanced subsurface biodegradation of hydrocarbons using hydrogen peroxide as an oxygen source. API Publication Number 4448. API, Washington, DC.

Anonymous. 1986. In situ reclamation of petroleum contaminated sub-soil by subsurface venting and enhanced biodegradation. Research Disclosure, No. 26233, 92-93.

Atlas, R.M. 1986. Microbial degradation of petroleum hydrocarbons: An environmental perspective. Microbiol. Rev. 45:180-209.

Baker, J.N., D.A. Nickerson, and P.R. Guest. 1993. Use of a horizontal air-dispersion system to enhance biodegradation of diesel fuel contaminated sites. In: Proceedings of the 1993 Petroleum Hydrocarbons and Organic Chemicals in Ground Water Prevention, Detection, and Restoration Conference (November 10-12), presented by the American Petroleum Institute and the Association of Ground Water Scientists and Engineers. Dublin, OH: Water Well Journal Publishing Company.

Battelle. 1994. Bioremediation of hazardous wastes at CERCLA and RCRA sites: Hill AFB 280 Site, low-intensity bioreclamation. Prepared by Battelle Memorial Institute for the U.S. EPA.

Bennedsen, M.B., J.P. Scott, and J.D. Hartley. 1987. Use of vapor extraction systems for in situ removal of volatile organic compounds from soil. In: Proceedings of the National Conference on Hazardous Wastes and Hazardous Materials, Washington, DC. pp. 92-95.

Bilbo, C.M., E. Arvin, and H. Holst. 1992. Modelling the growth of methane-oxidizing bacteria in a fixed biofilm. Water Res. 26:301-309.

Britton, L.N. 1985. Field studies on the use of hydrogen peroxide to enhance microbial degradation of gasoline. American Petroleum Institute Publication Number 4389. API, Washington, DC.

Brock, T.D., D.W. Smith, and M.T. Madigan. 1984. Biology of microorganisms, 4th ed. Englewood Cliffs, NJ: Prentice-Hall, Inc.

Brown, R.A., and J.R. Crosbie. 1994. Oxygen sources for in situ bioremediation. In: Bioremediation field experience. Boca Raton, FL: Lewis Publishers. pp. 311-331.

Brown, R.A., R.D. Norris, and R.L. Raymond. 1984. Oxygen transport in contaminated aquifers. In: Proceedings of the NWWA/API Conference on Petroleum Hydrocarbons and Organic Chemicals in Groundwater (November). National Water Well Association, Columbus, OH.

Conner, A.T. 1989. Case study on soil venting. Poll. Eng. 20(8):74-78.

DeVinny, J.S. L.G. Everett, J.C.S. Lu, and R.L. Stollar. 1990. Subsurface migration of hazardous wastes. New York, NY: Van Nostrand Reinhold.

Downey, D.C., and J.F. Hall. 1994. Addendum one to test plan and technical protocol for a field treatability test for bioventing—Using soil gas surveys to determine bioventing feasibility and natural attenuation potential. U.S. Air Force Center for Environmental Excellence, Brooks Air Force Base, TX.

Downey, D.C., J.F. Hall, R.N. Miller, A. Leeson, and R.E. Hinchee. 1994. Bioventing performance and cost summary, February, 1994. U.S. Air Force Center for Environmental Excellence, Brooks Air Force Base, TX.

Downey, D.C., R.E. Hinchee, M.S. Westray, and J.K. Slaughter. 1988. Combined biological and physical treatment of a jet fuel-contaminated aquifer. In: Proceedings of the NWWA/API Conference on Petroleum Hydrocarbons and Organic Chemicals in Groundwater (November). National Water Well Association, Columbus, OH. pp. 627-645.

Dragun, J. 1988. Microbial degradation of petroleum products in soil. In: Calabrese, E.J., and P.T. Kostecki, eds. Soils contaminated by petroleum: Environmental and public health effects. New York, NY: John Wiley & Sons, Inc. pp. 289-300.

Dupont, R.R., W.J. Doucette, and R.E. Hinchee. 1991. Assessment of in situ bioremediation potential and the application of bioventing at a fuel-contaminated site. In: Hinchee, R.E., and R.F. Olfenbuttel, eds. In situ bioreclamation: Applications and investigations for hydrocarbon and contaminated site remediation. Stoneham, MA: Butterworth-Heinemann Publishing Company. pp. 262-282.

Hinchee, R.E., and M. Arthur. 1991. Bench-scale studies of the soil aeration process for bioremediation of petroleum hydrocarbons. J. Appl. Biochem. Biotech. 28/29:901-906.

Hinchee, R.E., D.C. Downey, and P. Aggarwal. 1991a. Use of hydrogen peroxide as an oxygen source for in situ biodegradation: Part I, Field studies. J. Hazardous Materials 27:287-299.

Hinchee, R.E., D.C. Downey, and T. Beard. 1989a. Enhancing biodegradation of petroleum hydrocarbon fuels in the vadose zone through soil venting. In: Proceedings of the 1993 Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Restoration Conference (November 10-12), presented by the American Petroleum Institute and the Association of Ground Water Scientists and Engineers. Dublin, OH: Water Well Journal Publishing Company. pp. 235-248.

Hinchee, R.E., D.C. Downey, R.R. Dupont, P. Aggarwal, and R.N. Miller. 1991b. Enhancing biodegradation of petroleum hydrocarbon through soil venting. J. Hazardous Materials 27:315-325.

Hinchee, R.E., D.C. Downey, J.K. Slaughter, D.A. Selby, M. Westray, and G.M. Long. 1989b. HQ AFESC/RDVW ESK-TR-88-78. Enhanced bioreclamation of jet fuels: A full-scale test at Eglin Air Force Base, Florida. ESL/TR/88-78. Air Force Engineering and Services Center.

Hinchee, R.E., and S.K. Ong. 1992. A rapid in situ respiration test for measuring aerobic biodegradation rates of hydrocarbons in soil. J. Air & Waste Management Association 42(10):1305-1312.

Hinchee, R.E., S.K. Ong, R.N. Miller, D.C. Downey, and R. Frandt. 1992. Test plan and technical protocol for a field treatability test for bioventing, Rev. 2. U.S. Air Force Center for Environmental Excellence, Brooks Air Force Base, TX.

Hinchee, R.E., and G. Smith. 1991. Unpublished data. Battelle Memorial Institute, Columbus, OH.

Hopkins, G.D., J. Munakata, L. Semprini, and P.L. McCarty. 1993. Trichloroethylene concentration effects on pilot field-scale in-situ groundwater bioremediation by phenol-oxidizing microorganisms. Environ. Sci. Tech. 27(12):2542-2547.

Howard, P.H., R.S. Boethling, W.F. Jarvis, W.M. Meylan, and E.M. Michalenko. 1991. Handbook of environmental degradation rates. Chelsea, MI: Lewis Publishers.

Johnson, P.C., M.W. Kemblowski, and J.D. Colthart. 1990. Quantitative analysis for the cleanup of hydrocarbon-contaminated soils by in-situ soil venting. Ground Water 28(3).

Kittel, J.A., R.E. Hinchee, and M. Raj. 1995. Full-scale startup of a soil venting-based in situ bioremediation field pilot study at Fallon NAS, Nevada. Report prepared for the Naval facilities Engineering Services, Port Hueneme, CA (February).

Leeson, A., and R.E. Hinchee. 1994. Field treatability study at the Greenwood Chemical Superfund Site, Albemarle County, Virginia. Report prepared for the U.S. EPA, Cincinnati, OH (January).

Leeson, A., R.E. Hinchee, J.A. Kittel, E.A. Foote, G. Headington, and A. Pollack. 1995. Bioventing feasibility study at the Eielson AFB Site. Report prepared for the Environics Directorate of the Armstrong Laboratory, Tyndall AFB, FL (September).

Lund, N.-C., J. Swinianski, G. Gudehus, and D. Maier. 1991. Laboratory and field tests for a biological in situ remediation of a coke oven plant. In: Hinchee, R.E., and R.F. Olfenbuttel, eds. In situ bioreclamation: Applications and investigations for hydrocarbon and contaminated site remediation. Stoneham, MA: Butterworth-Heinemann Publishing Company.

Lyman, W.J., P.J. Reidy, and B. Levy. 1992. Mobility and degradation of organic contaminants in subsurface environments. Chelsea, MI: C.K. Smoley, Inc.

Metcalf and Eddy. 1979. Wastewater engineering treatment, disposal, reuse. New York, NY: McGraw-Hill.

Miller, R.N. 1990. A field scale investigation of enhanced petroleum hydrocarbon biodegradation in the vadose zone combining soil venting as an oxygen source with moisture and nutrient additions. Ph.D. Dissertation. Utah State University, Logan, UT.

Miller, R.N., D.C. Downey, V.A. Carmen, R.E. Hinchee, and A. Leeson. 1993. A summary of bioventing performance at multiple Air Force sites. In: Proceedings of the 1993 Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Restoration Conference (November 10-12), presented by the American Petroleum Institute and the Association of Ground Water Scientists and Engineers. Dublin, OH: Water Well Journal Publishing Company.

Miller, R.N., C.C. Vogel, and R.E. Hinchee. 1991. A field-scale investigation of petroleum hydrocarbon biodegradation in the vadose zone enhanced by soil venting at Tyndall AFB, Florida. In: Hinchee, R.E., and R.F. Olfenbuttel, eds. In situ bioreclamation: Applications and investigations for hydrocarbon and contaminated site remediation. Stoneham, MA: Butterworth-Heinemann Publishing Company. pp. 283-302.

Morgan, P., and R.J. Watkinson. 1992. Factors limiting the supply and efficiency of nutrient and oxygen supplements for the in situ biotreatment of contaminated soil and groundwater. Wat. Research 26(1):73-78.

Mormile, M.R., S. Liu, and J.M. Suflita. 1994. Anaerobic biodegradation of gasoline oxygenates: extrapolation of information to multiple sites and redox conditions. Environ. Sci. Tech. 28(9):1727-1732.

Newman, B. M. Martinson, G. Smith, and L. McCain. 1993. Enhanced biodegradation of hydrocarbons in-situ via bioventing. In: Proceedings of the 1993 Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Restoration Conference (November 10-12), presented by the American Petroleum Institute and the Association of Ground Water Scientists and Engineers. Dublin, OH: Water Well Journal Publishing Company.

Oak Ridge National Laboratory. 1989. Soil characteristics: Data summary, Hill Air Force Base Building 914 fuel spill soil venting project. Draft report to the U.S. Air Force.

Ong, S.K., A. Leeson, R.E. Hinchee, J. Kittel, C.M. Vogel, G.D. Sayles, and R.N. Miller. 1994. Cold climate application of bioventing. In: Hinchee, R.E., B.C. Alleman, R.E. Hoeppel, and R.N. Miller, eds. Hydrocarbon bioremediation. Boca Raton, FL: Lewis Publishers. pp. 444-453.

Ostendorf, D.W., and D.H. Kambell. 1989. Vertical profiles and near surface traps for field measurement of volatile pollution in the subsurface environment. In: Proceedings of the NWWA Conference on New Techniques for Quantifying the Physical and Chemical Properties of Heterogeneous Aquifers, Dallas, TX.

Phelps, M.B., F.T. Stanin, and D.C. Downey. 1995. In: Hinchee, R.E., R.N. Miller, and P.C. Johnson, eds. In situ aeration: Air sparging, bioventing and related remediation processes. Columbus, OH: Batelle Press. pp. 277-282.

Schumb, W.C., C.N. Satterfield, and R.L. Wentworth. 1955. Hydrogen peroxide. New York, NY: Van Nostrand Reinhold.

Spain, J.C. J.D. Milligan, D.C. Downey, and J.K. Slaughter. 1989. Excessive bacterial decomposition of H_2O_2 during enhanced biodegradation. J. Groundwater 27:163-167.

Staatsuitgeverij. 1986. Proceedings of a Workshop, 20-21 March, 1986. Bodembeschermingsreeeks No. 9; Biotechnologische Bodemsanering, pp. 31-33. Rapportnr. 851105002, ISBN 90-12-054133, Ordernr. 250-154-59; Staatsuitgeverij Den Haag: The Netherlands.

Texas Research Institute. 1984. Forced venting to remove gasoline vapor from a large-scale model aquifer. American Petroleum Institute, Final Report No. 8210l-F:TAV.

Texas Research Institute. 1980. Laboratory scale gasoline spill and venting experiment. American Petroleum Institute, Interim Report No. 7743-5:JST.

Urlings, L.G.C.M., H.B.R.J. van Vree, and W. van der Galien. 1990. Application of biotechnology in soil remediation. Envirotech Vienna. pp. 238-251.

U.S. EPA. 1994a. Bioventing soils contaminated with wood preservatives. Presented at: Symposium on Bioremediation of Hazardous Wastes: Research, Development, and Field Evaluations (June). EPA/600/R-94/075. Washington, DC.

U.S. EPA. 1994b. Bioventing of jet fuel spills II: Bioventing in a deep vadose zone at Hill AFB, Utah. Presented at: Symposium on Bioremediation of Hazardous Wastes: Research, Development and Field Applications (June). EPA/600/R-94/075. Washington, DC. pp. 22-28.

U.S. EPA. 1994c. Bioventing of jet fuel spills I: Bioventing in a cold climate with soil warming at Eielson AFB, Alaska. Presented at: Symposium on Bioremediation of Hazardous Wastes: Research, Development and Field Applications (June). EPA/600/R-94/075. Washington, DC. pp. 15-21.

U.S. EPA. 1993. Engineering issue—In situ bioremediation of contaminated unsaturated subsurface soils. Draft report. EPA/540/S-93/501. Washington, DC.

U.S. EPA. 1990. Enhanced biodegradation utilizing hydrogen peroxide as a supplemental source of oxygen: A laboratory and field study. EPA/600/2-90/006. Washington, DC.

van Eyk, J., and C. Vreeken. 1989a. Model of petroleum mineralization response to soil aeration to aid in site-specific, in situ biological remediation. In: Jousma et al., eds. Groundwater contamination: Use of models in decision-making, Proceedings of the International Conference on Groundwater Contamination. Boston/London: Kluwer. pp. 365-371.

van Eyk, J., and C. Vreeken. 1989b. Venting-mediated removal of diesel oil from subsurface soil strata as a result of stimulated evaporation and enhanced biodegradation. In: Hazardous Waste and Contaminated Sites, Envirotech Vienna, Vol. 2, Session 3. ISBN 389432-009-5. Westarp Wiss., Essen, Germany. pp. 475-485.

van Eyk, J., and C. Vreeken. 1988. Venting-mediated removal of petrol from subsurface soil strata as a result of stimulated evaporation and enhanced biodegradation. Med. Fac. Landbouww. Riiksuniv. Gent 53(4b):1873-1884.

Wackett, L.P., and D.T. Gibson. 1992. Degradation of trichloroethylene by toluene dioxygenase in whole-cell studies with *Pseudomonas putida* F1. Applied and Environmental Microbiology 54(7):1703-1708.

Ward, C.H. 1988. A quantitative demonstration of the Raymond process for in-situ biorestoration of contaminated aquifers. In: Proceedings of the NWWA/API Conference on Petroleum Hydrocarbons and Organic Chemicals in Groundwater. pp. 723-746.

Wilson, J.T., and C.H. Ward. 1986. Opportunities for bioremediation of aquifers contaminated with petroleum hydrocarbons. J. Ind. Microbiol. 27:109-116.

Zachary, S.P., and L.G. Everett. 1993. In-situ active/passive bioreclamation of vadose zone soils contaminated with gasoline and waste oil using soil vapor extraction/bioventing: Laboratory pilot study to full scale site operation. In: Proceedings of the 1993 Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Restoration Conference (November 10-12), presented by the American Petroleum Institute and the Association of Ground Water Scientists and Engineers. Dublin, OH: Water Well Journal Publishing Company.

Appendix A
Glossary

abiotic not relating to living things, not alive

acidity measure of the hydrogen ion concentration of a solution

adsorption process by which molecules collect on and adhere to the surface of an adsorbent solid because of chemical and/or physical forces

aeration process of supplying or introducing air into a medium such as soil or water

aerobic living, active, or occurring only in the presence of oxygen

air sparging technology of introducing gases, usually air, beneath the water table to promote site remediation; air sparging can be divided into two distinct processes: in-well aeration and air injection

alkalinity measure of the hydroxide ion concentration of a solution

alluvial relating to flowing water, as in a stream or river

anaerobic living, active, or occurring only in the absence of oxygen

aquifer water-bearing layer of permeable rock, sand, or gravel

bentonite clay composed of volcanic ash decomposition, which is used to seal wells

bioavailability accessibility of contaminants to the degrading populations; consists of (1) a physical aspect related to phase distribution and mass transfer and (2) a physiological aspect related to the suitability of the contaminant as a substrate

biodegradable material or compound that can be broken down by natural processes of living things such as metabolization by microorganisms

biodegradation act of breaking down material (usually into more innocuous forms) by natural processes of living things such as metabolization by microorganisms

biofilm structure in which bacteria fixed to a surface produce a protective extracellular polysaccharide layer

biofiltration process using microorganisms immobilized as a biofilm on a porous filter substrate, such as peat or compost, to separate contaminants; as air and vapor contaminants pass through the filter, contaminants transfer from the gas phase to the biolayer, where they are metabolized

biomass amount of living matter (in a specified area)

bioreactor container or area in which a biological reaction or biological activity takes place

bioreclamation process of making a contaminated site usable again through biological processes

bioremediation technology of using biological processes such as microbial metabolism to degrade soil and water contaminants and decontaminate sites

bioslurping technology application that teams vacuum-assisted free-product recovery with bioventing to simultaneously recover free product and remediate the vadose zone

bioventing process of aerating subsurface soils by means of installed vents to stimulate in situ biological activity and optimize bioremediation, with some volatilization occurring

capillarity action by which a liquid is held to a solid by surface tension

capillary fringe first layer of rock above a layer in which water is held by capillarity

catalyst substance that initiates a chemical reaction, allows a reaction to proceed under different conditions than otherwise possible, or accelerates a chemical reaction; catalysts are not consumed in the reaction; enzymes are catalysts

catalytic oxidation incineration process that uses catalysts to increase the oxidation rate of organic contaminants, allowing equivalent destruction efficiency at a lower temperature than flame incineration

clay fine-grained soil that can exhibit putty-like properties within a range of water content and is very strong when air-dried

cometabolic process metabolism of a less-favored substrate occurring during the metabolism of the primary substrate

cone of depression area of lowered water table around a well site because of active pumping

contaminant something that makes material in contact with it impure, unfit, or unsafe; a pollutant

diffusion process of passive transport through a medium motivated by a concentration gradient

diffusivity diffusion coefficient; the amount of material, in grams, that diffuses across an area of 1 cm^2 in 1 second because of a unit concentration gradient (articular to compound and medium pair)

electron acceptor relatively oxidized compound that takes electrons from electron donors during cellular respiration, resulting in the release of energy to the cell

electron donor organic carbon, or reduced inorganic compound, that gives electrons to electron acceptors during cellular respiration, resulting in the release of energy to the cell

enzyme biologically produced, protein-based catalyst

ex situ refers to a technology or process for which contaminated material must be removed from the site of contamination for treatment

facultative microbial trait enabling aerobic or anaerobic respiration, depending on environment

head pressure difference between two places; an energy term expressed in length units

immiscible refers to liquids that do not form a single phase when mixed (e.g., oil and water)

in situ refers to a technology or treatment process that can be carried out within the site of contamination

in situ respiration test test used to provide rapid field measurement of in situ biodegradation rates to determine the potential applicability of bioventing at a contaminated site and to provide information for a full-scale bioventing system design

in-well aeration process of injecting gas into a well to produce an in-well airlift pump effect

miscible refers to liquids that form a single phase when mixed (e.g., ethanol and water)

nitrogen fixation metabolic assimilation of atmospheric nitrogen by soil microorganisms and release of the nitrogen for plant use upon the death of the microorganisms

nutrients constituents required to support life and growth

off-gas gas that leaves a site, typically from a point source during extraction operations

oxidation chemical process that results in a net loss of electrons in an element or compound

oxygen utilization rate rate of reduction of the in situ oxygen content of soil gas because of biological and chemical action

ozonation injection of ozone into a contaminated site

packed-bed thermal treatment process that oxidizes organic contaminants by passing the off-gas stream through a heated bed of ceramic beads, resulting in destruction of the organic compounds

perched aquifer unconfined ground water separated from an underlying main body of ground water by a low-permeability rock layer that blocks vertical movement of water

permeability measure of the ability of liquid or gas to move through pores and openings in a material

pH measure of the alkalinity or acidity of a solution; the negative log of the hydrogen ion concentration

photocatalytic oxidation process by which volatile organic compounds are converted to carbon dioxide and water by exposure to ultraviolet light

pore space open space in a material through which liquid and gas can move

porosity measure of the amount of available space in a material through which liquid and gas can move

primary substrate substrate that provides most of the growth and energy requirements for cells

pump and treat technology treatment method in which the contaminated water is pumped out of the contaminated site, then treated off site before being returned

radius of influence maximum distance from the air extraction or injection well where vacuum or pressure (soil gas movement) occurs

radius of oxygen influence radius to which oxygen has to be supplied to sustain maximal biodegradation; a function of air flow rates and oxygen utilization rates and, therefore, depends on site geology, well design, and microbial activity

Raoult's law physical chemical law that states that the vapor pressure of a solution is equal to the mole fraction of the solvent multiplied by the vapor pressure of the pure solvent

reduction chemical process that results in a net gain of electrons to an element or compound

remediation activity involved with reducing the hazard from a contaminated site

sand unconsolidated rock and mineral particles with diameters ranging from 1/16 mm to 2 mm

silt unconsolidated rock and mineral particles with diameters ranging from 0.0002 mm to 0.05 mm

soil gas permeability soil's capacity for fluid flow; varies according to grain size, soil uniformity, porosity, and moisture content

soil vacuum extraction (SVE) process designed and operated to maximize the volatilization of low-molecular-weight compounds, with some biodegradation occurring

sorb to take up or hold by means of adsorption or absorption

substrate base on which an organism lives; reactant in microbial respiration reaction (electron donor, nutrient)

surfactant substance that lowers the surface tension of a liquid

treatability ability of a site to be remediated

vacuum-enhanced pumping use of a vacuum pump to lift ground water, or other liquids or gases, from a well while producing a reduced pressure in the well

vadose zone zone of soil below the surface and above the permanent water table

volatile easily vaporized at relatively low temperatures

volatilization process of vaporizing a liquid into a gas

Appendix B
Data From Bioventing Initiatives Sites

Table B-1. Bioventing Initiative Results: Soil Chemical Characterization

Air Force Base	Site	pH	Alkalinity (mg/kg)	TKN (mg/kg)	Total Phosphorus (mg/kg)	Iron Content (mg/kg)
AFP 4	FSB-1	8.8	210	33	270	7,450
	FSA-3	7.7	365	190	340	9,800
AFP PJKS	ST-35	7.5	NS	490	46	NS
Battle Creek	Fire Training Area	8.2	170	73	165	5,050
Beale	Site 3	7.7	87	105	400	27,500
	Site 18	7.4	67	42	250	26,400
	Site 11	8.2	240	15	820	17,500
Bolling	Building 18	4.9	<50	48	85	15,300
	Former Storage Tank Farm	8.1	910	100	170	9,610
Camp Pendleton	Site 1	7.7	120	73	46	3,360
Cannon	SWMU 70	8.4	1,150	190	76	6,570
Cape Canaveral	FTA-2	7.7	165	18	280	860
	Facility 1748	8.5	400	110	310	900
	Facility 44625D	9.2	265	74	190	1,380
	Facility 44625E	8.8	350	54	270	970
Charleston	FT-03	7.1	280	350	350	2,940
	Site ST-27	6.7	130	62	75	8,400
	Site SS-41	4.7	<50	61	37	530
Davis Monthan	Site 35	8.3	360	32	760	15,700
	Site 36	8.1	220	57	450	12,700
Dover	ST-04	5.3	36	48	270	4,700
	North Storage Tank Farm	5.5	<50	410	100	8,740
Dyess	Site FT40	8.7	3,130	180	200	16,900
	Site FT41	8.8	2,790	240	280	19,500
Edwards	Site 21	9.3	730	26	650	9,960
	Site 16	9.6	640	22	630	12,500
	Site 43	8.9	500	150	360	13,400
Eglin	FTA Hurleburt Field	8.2	300	74	33	670
	Old Eglin FTA	7.5	170	<43	24	1,600
Eielson	ST-10	6.3	<50	390	7.4	10,400
	Site 48-E2	7.8	240	320	650	17,400
	Site 48-E3	7.5	230	690	790	16,700

Table B-1. Bioventing Initiative Results: Soil Chemical Characterization (Continued)

Air Force Base	Site	pH	Alkalinity (mg/kg)	TKN (mg/kg)	Total Phosphorus (mg/kg)	Iron Content (mg/kg)
Ellsworth	Area D Bulk Fuel Storage	8.5	1,150	320	500	15,000
	Building 102 Base Fuel Station	8.6	640	24	1,000	36,800
Elmendorf	43/45 Valve Pit	7.2	100	64	3.5	24,800
	ST-61	7.7	160	78	1,200	23,700
	ST-71	7.8	200	110	3.1	28,000
	43/55 Pumphouse	7.5	87	66	1,200	25,300
FE Warren	Fire Training Pit	7.8	1,300	1,300	440	20,200
	Spill Site	8.2	340	55	320	11,200
Galena	Saddle Tank Farm	7.5	520	800	730	21,400
	Power Plant	7.8	490	620	710	24,200
	Million Gallon Hill	NS	NS	NS	NS	NS
	Campion POL Leak Site	8.1	300	710	570	15,200
Hanscom	Building 1639	6.0	<50	630	320	7,620
	Building 1812	6.6	58	60	530	6,810
Hickam	Area H	9.0	1,500	30	3,400	75,100
	Area K	8.3	860	1,700	2,300	34,100
	Site 2 FSA	4.7	35	38	470	99,000
Hill	Site 204.1	7.8	740	140	NS	5,270
	Site 214.1	NS	NS	NS	NS	NS
	Site 228	NS	NS	NS	NS	NS
	Site 924	8.0	74	120	710	6,500
	Site 1705	NS	NS	NS	NS	NS
	Site 388	6.8	52	350	NS	9,380
	Site 40002	NS	NS	NS	390	NS
	Site 510.8	8.7	340	100	2,200	4,700
Johnston Island	Old Fire Training Area	8.9	540	440	370	270
	Former POL Tank Farm	9.0	405	185	520	115
	Storage Tanks 260 and 261	9.0	355	140	340	84
Keesler	SWMU 66	7.5	260	102	190	4,300
	AOC A	7.0	250	43	35	2,100
Kelly	Site S-4	7.5	500	690	620	16,000
	Site FC-2	8.2	750	590	790	13,400
	Site B-2093	8.2	1,100	310	880	14,000
	Site D-10	7.7	1,100	640	310	13,300
Kirtland	Fire Training Area 13	8.4	340	58	300	11,200
	Fire Training Area 14	7.0	380	200	1,000	26,200
KI Sawyer	POL Area	7.9	98	22	140	2,190
Kodiak Island	Tank 191	7.0	260	590	930	24,900
Little Rock	Fire Training Site 1	6.1	86	710	130	53,000
	Spill Site 18	6.1	<50	390	140	36,300
Los Angeles	Building 125	8.7	440	87	1,200	8,900
	Building 241	7.5	830	120	1,600	33,800
	Gate 3	8.4	310	65	1,400	18,700
March	IRP Site 35c	8.2	21	130	280	32,200

Table B-1. Bioventing Initiative Results: Soil Chemical Characterization (Continued)

Air Force Base	Site	pH	Alkalinity (mg/kg)	TKN (mg/kg)	Total Phosphorus (mg/kg)	Iron Content (mg/kg)
McClellan	Building 720	7.5	22.5	44	260	11,400
	Davis Site	8.0	350	260	400	40,200
	Capehart Gas Station	5.8	95	54	180	26,700
	PRL T-46	7.4	46	50	5.9	21,300
	Study Area 6	8.0	71	10	590	28,400
	Tank Farm #2	7.8	120	47	1,100	26,700
	Tank Farm #4	7.4	100	74	150	25,200
McGuire	Bulk Fuel Storage	6.1	37	480	217	5,830
Mt. Home	POL Yard	8.4	2,100	76	5.0	21,100
Nellis	Site 27	8.8	1,600	260	170	6,950
	Site 28	8.6	410	100	290	5,800
	Site 44	8.5	800	53	210	6,800
Newark	Facility 27	7.8	370	35	515	15,400
	Facility 89	7.8	460	360	540	16,100
	Facility 14	7.9	320	200	260	16,400
Offutt	Low Point Drain	8.0	330	190	480	7,500
	Building 30	8.7	1,600	250	680	13,700
	Building 406	7.8	360	220	720	18,500
	POL Storage Area	7.9	470	750	600	9,800
Patrick	FTA-2	8.8	220	32	260	440
	BX Service Station	8.4	160	60	290	360
Pease	Bulk Fuel Storage Area	6.6	140	190	730	21,000
	Site 2	5.7	22.5	59	630	39,100
Plattsburgh	Fire Training Area 1	6.6	84	75	<1.0	4,500
	Fire Training Pit 4	6.4	22	36	330	4,500
	Fire Training Areas 2 and 3	7.6	120	49	160	4,200
Pope	IRP Site ST-08	6.7	200	<40	110	3,000
Randolph	Tank 20 Site	8.1	340	230	920	12,400
Robins	UST 173	5.2	<50	90	84	6,000
	SS10	5.3	<50	46	78	3,600
Shaw	Site FT-01	5.6	22	190	38	4,100
	Site SS-15	5.2	22	20	260	13,900
Tinker	POL Storage Area C	7.3	<50	30	55	3,210
Travis	Fuel Storage Area G	7.4	120	79	220	28,400
	South Gas Station	7.9	120	210	300	22,100
Vandenburg	Service Station	6.9	20	103	100	2,920
	JP-4 Site	6.1	180	57	100	9,700
Westover	Building 7701	6.1	<50	61.5	580	6,835
	Building 7705	6.8	22	200	190	4,900
Wright Patterson	Fire Training Area	7.2	730	680	570	16,200
	Spill Sites 2 and 3	8.1	340	<20	310	6,900

NS = not sampled.

Table B-2. Preliminary Bioventing Initiative Results: Average BTEX and TPH Soil Concentrations

			Soil Analysis						
Air Force Base	Site	Time	Benzene (mg/kg)	Toluene (mg/kg)	Ethyl-benzene (mg/kg)	Total Xylenes (mg/kg)	Total BTEX (mg/kg)	TPH (mg/kg)	Moisture Content (%)
AFP 4	FSA-1	Initial	0.36	1.3	12	31	45	29	13.7
		Final	BDL	BDL	BDL	BDL	BDL	680	14.7
	FSA-3	Initial	2.7	9.1	7.1	60	79	140	16.2
		Final	BDL	BDL	BDL	BDL	BDL	84	15.4
AFP PJKS	ST-35	Initial	BDL	BDL	0.73	1.5	2.2	1,100	8.9
		Final	BDL	BDL	BDL	BDL	BDL	130	11.9
Battle Creek	Fire Training Area	Initial	0.43	3.0	2.6	12	23	7,200	4.8
		Final	BDL	BDL	BDL	0.016	0.016	1,800	5.0
Beale	Site 3	Initial	1.5	4.8	3.5	17	26.20	14,000	23.8
		Final	BDL	BDL	0.41	1.4	1.81	10,100	20.9
	Site 18	Initial	BDL	1.1	2.5	6.0	9.6	17,000	22.8
		Final	BDL	BDL	BDL	BDL	BDL	5,600	19.8
	Site 11	Initial	1.4	50	24	175	253	400	16.8
		Final	0.6	0.61	4.4	240	246	1,600	12.5
Bolling	Building 18	Initial	BDL	BDL	2.0	1.8	3.80	1,800	16.0
		Final	BDL	BDL	BDL	BDL	BDL	4,100	6.1
	Former Storage Tank Farm	Initial	0.27	8.4	1.5	3.7	13.87	72	15.7
		Final	0.064	BDL	0.12	0.22	0.40	160	15.5
Camp Pendleton	Site 1	Initial	0.028	0.072	0.45	0.50	1.05	3,400	11.0
Cannon	SWMU 70	Initial	1.5	14	14	53	83	2,700	12.4
Cape Canaveral	FTA-2	Initial	BDL	4.2	2.6	6.6	13.40	300	14.3
		Final	BDL	BDL	BDL	BDL	BDL	1,100	NR
	Facility 1748	Initial	0.58	0.58	2.0	5.7	8.86	17,200	9.2
	Facility 44625D	Initial	0.35	0.35	0.35	1.3	2.4	10,500	6.4
	Facility 44625E	Initial	0.40	0.51	0.61	7.1	8.62	9,200	6.4
Charleston	FT-03	Initial	BDL	2.0	0.82	2.3	5.12	1,100	15.8
		Final	BDL	BDL	BDL	BDL	BDL	790	8.1
	ST-27	Initial	BDL	0.0056	0.0033	0.015	0.02	15	13.9
	Site SS-41	Initial	0.70	28	2.2	17	47.90	730	14.6
Davis Monthan	Site 35	Initial	3.3	16	14	23	56	530	9.4
	Site 36	Initial	20	100	63	140	323.00	2,700	7.2
Dover	ST-04	Initial	0.90	1.1	1.7	8.7	12.40	8.7	11.7
		Final	BDL	BDL	BDL	BDL	BDL	BDL	14.2
	North STF	Initial	BDL	0.33	13	37	50.33	1,200	24.9
		Final	BDL	0.25	0.080	0.19	0.52	650	22.0
Dyess	Site FT40	Initial	BDL	BDL	BDL	0.93	0.93	450	17.2
		Final	BDL	BDL	BDL	BDL	BDL	160	17.0
	Site FT41	Initial	0.05	0.05	0.05	0.07	0.22	930	16.6
		Final	BDL	BDL	BDL	BDL	BDL	200	15.4
Edwards	Site 21	Initial	BDL	0.13	1.6	6.5	6.20	110	11.1
		Final	BDL	BDL	BDL	BDL	BDL	23	10
	Site 16	Initial	0.24	0.29	2.3	12	14.59	24	13.7
		Final	BDL	BDL	BDL	BDL	BDL	5.1	13.3
	Site 43	Initial	BDL	BDL	0.12	0.68	0.95	540	9.4
		Final	BDL	BDL	BDL	BDL	BDL	74	1.65
Eglin	FTA HurlebURT Field	Initial	0.97	14	7.3	48	70.27	9,600	6.6
	Old Eglin FTA	Initial	3.8	7.5	11	32	54.30	4,100	6.9
Eielson	ST-10	Initial	BDL	230	41	340	611.00	4,100	12.3
		Final	BDL	0.015	0.0071	0.0050	0.027	52	2.7
	Site 48-E2	Initial	1.4	4.4	11	45	62	5,400	14.9
		Final	BDL	BDL	0.34	1.4	1.7	1,200	6.2
	Site 48-E3	Initial	BDL	4.3	BDL	4.6	8.90	2,600	27.8
		Final	BDL	BDL	BDL	BDL	BDL	21	36.9
Ellsworth	Area D Bulk Fuel Storage	Initial	8.2	8.9	37	190	244.10	2,800	17.7
		Final	0.842	BDL	1.8	10	12	2,800	16
	Building 102 Base Fuel Station	Initial	0.18	0.60	0.78	4.3	5.86	11	7.2
		Final	BDL	BDL	11	44	55	651	9.8

Table B-2. Preliminary Bioventing Initiative Results: Average BTEX and TPH Soil Concentrations (Continued)

			Soil Analysis						
Air Force Base	**Site**	**Time**	**Benzene (mg/kg)**	**Toluene (mg/kg)**	**Ethyl-benzene (mg/kg)**	**Total Xylenes (mg/kg)**	**Total BTEX (mg/kg)**	**TPH (mg/kg)**	**Moisture Content (%)**
Elmendorf	43/45 Valve Pit	Initial	BDL	BDL	BDL	BDL	BDL	4.9	5.6
		Final	BDL	32	32	140	200	6,000	9.8
	ST-61	Initial	BDL	0.019	0.30	0.34	0.66	790	8.4
		Final	BDL	0.098	0.22	0.75	1.1	2,400	11.6
	ST-71	Initial	BDL	BDL	BDL	BDL	BDL	32	4.6
		Final	BDL	0.001	BDL	0.00053	0.0015	26	5.1
	43/55 Pumphouse	Initial	1.7	41	52	241	330	3,900	8.1
		Final	BDL	BDL	BDL	BDL	BDL	4.9	4.6
FE Warren	Fire Training Pit	Initial	BDL	0.46	0.66	1.4	2.5	3,000	20.7
	Spill Site	Initial	BDL	BDL	4.8	31	36	400	20.8
		Final	BDL	4.1	BDL	10	14	700	19
Fort Drum	Area 1595	Initial	BDL	BDL	3.4	25	28	15,000	10.6
Galena	Saddle Tank Farm	Initial	BDL	0.85	BDL	3.7	4.6	270	21.9
	Power Plant	Initial	BDL	BDL	BDL	BDL	BDL	97	22.3
		Final	BDL	BDL	BDL	BDL	BDL	BDL	5.8
	Million Gallon Hill	Initial	NS	NS	NS	NS	NS	NS	NS
	Campion POL Leak Site	Initial	0.028	0.25	BDL	0.19	0.47	760	12.3
Hanscom	Building 1639	Initial	0.57	1.5	0.58	4.2	6.85	13	16.6
		Final	0.032	0.57	0.073	0.3	0.98	130	15.3
	Building 1812	Initial	BDL	0.026	BDL	0.047	0.03	6,500	4.7
		Final	BDL	0.016	BDL	0.023	0.039	1,800	3.1
Hickam	Area H	Initial	2.8	5.3	5.5	7.5	21.10	12	24.6
		Final	0.078	0.013	0.0049	0.0046	0.10	4.8	24.1
	Area K	Initial	1.1	12	10	19	34.04	20	15.5
		Final	BDL	BDL	BDL	BDL	BDL	47	13.7
	Site 2 FSA	Initial	0.6	11	7.4	38	71.74	1,100	33.7
		Final	0.93	3.5	11	12	27	1,400	31.8
Hill	Site 204.1	Initial	0.021	0.16	0.54	5.1	5.82	960	6.2
		Final	BDL	0.01	BDL	0.089	0.099	4,500	7.7
	Site 214.1	Initial	3.3	3.7	5.3	9.1	21	12,100	19
		Final	BDL	BDL	BDL	BDL	BDL	550	NS
	Site 228	Initial	0.64	9.2	7.1	240	256.94	5,800	11.7
		Final	BDL	BDL	BDL	BDL	BDL	BDL	8
	Site 924	Initial	BDL	BDL	BDL	BDL	BDL	BDL	6.7
		Final	BDL	BDL	0.0068	0.029	0.036	BDL	16.7
	Site 1705	Initial	BDL	BDL	BDL	0.12	0.12	4,400	8.3
		Final	BDL	BDL	BDL	BDL	BDL	600	6.3
	Site 388	Initial	1.9	43	25	250	320	7,500	8.7
		Final	0.045	0.046	0.54	4	4.6	1,100	6.9
	Site 40002	Initial	50	470	160	1,300	1,977.00	28,100	23.5
		Final	32	410	78	1,200	1,700	12,300	27
	Site 510.8	Initial	BDL	BDL	BDL	BDL	0.06	5,200	8.1
		Final	BDL	BDL	BDL	0.1	0.10	2,600	6.9
Johnston Atoll	Old Fire Training Area	Initial	BDL	0.65	BDL	BDL	0.45	7,700	11.0
	Former POL Tank Farm	Initial	BDL	BDL	3.5	2.5	6.0	13,000	10.7
	Storage Tanks 260 and 261	Initial	BDL	BDL	15	14	29.00	265	12.5
Keesler	SWMU 66	Initial	4.7	35	16	116	171.70	3,300	11.5
		Final	BDL	0.018	BDL	0.0050	0.023	2,500	34.1
	AOC A	Initial	0.10	0.039	0.22	0.080	0.44	87	8.4
		Final	BDL	0.0017	BDL	0.0020	0.0037	19	9.0
Kelly	Site S-4	Initial	BDL	9.1	BDL	13	20.20	920	21.1
		Final	BDL	0.94	BDL	1.5	2.4	590	22.9
	Site FC-2	Initial	BDL	8.0	BDL	22	30.00	1,600	20
		Final	0.014	0.13	0.014	0.022	0.18	64	20.5

Table B-2. Preliminary Bioventing Initiative Results: Average BTEX and TPH Soil Concentrations (Continued)

			Soil Analysis						
Air Force Base	**Site**	**Time**	**Benzene (mg/kg)**	**Toluene (mg/kg)**	**Ethyl-benzene (mg/kg)**	**Total Xylenes (mg/kg)**	**Total BTEX (mg/kg)**	**TPH (mg/kg)**	**Moisture Content (%)**
	Site B-2093	Initial	13	130	39	200	382.00	53	18.7
	Site D-10	Initial	BDL	0.0096	BDL	BDL	0.01	86	22.5
		Final	BDL	BDL	BDL	BDL	BDL	250	9.3
Kirtland	Fire Training Area 13	Initial	BDL	9.1	9.5	57	76	1,800	10.3
		Final	BDL	2.2	7.2	38	47	4,800	11.4
	Fire Training Area 14	Initial	BDL	BDL	0.79	3.7	4.49	7,900	11.3
KI Sawyer	POL Area	Initial	BDL	40	9.7	27	77.70	1,300	13.3
		Final	BDL	BDL	0.35	7.8	8.2	2,600	10.6
	FTA-06	Initial	0.72	7.5	7.8	36	52	6,700	5.8
		Final	0.84	2.2	3.6	11	18	8,200	4.9
	FTA-07	Initial	BDL	0.48	1.7	19	21	250	5.7
		Final	BDL	0.047	0.75	2.6	3.4	4,000	6.6
Kodiak UCSG	Tank 191	Initial	BDL	0.027	BDL	BDL	0.027	6.3	5.9
Little Rock	Fire Training Site 1	Initial	BDL	BDL	BDL	0.43	0.43	990	19.0
	Spill Site 18	Initial	BDL	BDL	0.53	0.74	1.27	8.2	16.3
		Final	BDL	BDL	BDL	BDL	BDL	BDL	16.1
Los Angeles	Building 125	Initial	BDL	BDL	BDL	BDL	BDL	560	9.6
	Building 241	Initial	0.0054	0.018	0.35	0.36	0.73	3,700	17.1
	Gate 3	Initial	0.031	0.23	1.4	2.3	3.96	4,000	15.4
Malmstrom	Pumphouse 2	Initial	BDL	0.71	1.6	3.7	6.0	240	22
		Final	BDL	0.067	0.21	0.13	0.41	84.6	ND
	Bulk POL	Initial	4.7	130	22	120	280	2,700	NS
March	IRP Site 35c	Initial	0.011	0.011	0.050	0.16	0.23	1,000	3.5
		Final	BDL	BDL	BDL	BDL	BDL	8.6	3.2
McClellan	Building 720	Initial	0.10	0.10	0.10	8.2	8.50	3,800	12
	Capehart Gas Station	Initial	1.0	1.6	0.12	0.84	3.56	5.4	17.1
	Davis Site	Initial	0.13	0.13	0.13	0.25	0.64	6,000	18.3
		Final	BDL	BDL	0.077	0.15	0.23	1,200	17.6
	PRL T-46	Initial	0.0022	0.0022	0.94	1.2	2.14	3,100	21.3
		Final	BDL	BDL	BDL	BDL	BDL	61	14.2
	Study Area 6	Initial	4.2	18	14	27	63.20	1,200	17.0
		Final	0.098	0.11	0.51	1.1	1.8	BDL	20.1
	Tank Farm #2	Initial	0.0065	1.6	0.12	0.57	2.30	37	15.3
		Final	BDL	BDL	0.11	BDL	0.11	98	13.5
	Tank Farm #4	Initial	0.017	0.029	0.017	1.1	1.16	41	20.7
		Final	BDL	BDL	BDL	BDL	BDL	BDL	22.5
McGuire	Bulk Fuel Storage	Initial	5.6	110	120	200	435.30	2,100	15.7
		Final	BDL	0.92	3.1	12	16	1,600	14.9
Mt. Home	POL Yard	Initial	84	440	82	930	1,536.00	5,800	15.7
Nellis	Site 27	Initial	0.39	1.9	1.0	4.7	7.99	50	14.0
		Final	8.1	33	18	67	130	7,800	19.4
	Site 28	Initial	14	65	30	130	239.00	2,200	24.1
		Final	2.2	11	8.1	25	46	1,500	21.2
	Site 44	Initial	1.2	53	28	110	192.20	300	24.9
		Final	0.40	2.6	1.1	5.5	9.6	140	18.9
Newark	Facility 27	Initial	BDL	BDL	BDL	BDL	BDL	43	16.1
		Final	0.0028	0.0079	BDL	0.0019	0.013	92	NR
	Facility 89	Initial	BDL	BDL	BDL	BDL	BDL	12	18.9
		Final	BDL	0.014	BDL	0.0011	0.015	6	NR
Offutt	Low Point Drain	Initial	0.11	1.8	1.0	6.3	9.2	15	15.7
	Building 406	Initial	2.2	1.4	21	35	60	730	23.0
		Final	0.048	0.88	0.034	1.8	2.8	1,600	20.0
	Building 30	Initial	BDL	0.0029	BDL	0.014	0.02	6.6	24.3
		Final	BDL	0.0041	BDL	0.00053	0.0046	BDL	22.4

Table B-2. Preliminary Bioventing Initiative Results: Average BTEX and TPH Soil Concentrations (Continued)

			Soil Analysis						
Air Force Base	**Site**	**Time**	**Benzene (mg/kg)**	**Toluene (mg/kg)**	**Ethylbenzene (mg/kg)**	**Total Xylenes (mg/kg)**	**Total BTEX (mg/kg)**	**TPH (mg/kg)**	**Moisture Content (%)**
	POL Storage Area	Initial	0.0042	0.00082	0.019	0.028	0.05	4.3	19
		Final	BDL	BDL	0.004	0.0073	0.011	5.5	21
Patrick	FTA-2	Initial	3.4	26	190	920	1,100	930	6.6
		Final	BDL	BDL	0.034	BDL	0.034	6,500	8.3
	BX Service Station	Initial	4.5	0.72	3.0	18	26	10,500	4.1
		Final	0.60	0.067	0.07	0.2	0.94	63	7.6
Pease	Bulk Fuel Storage Area	Initial	0.33	1.1	5.2	15	21.63	310	12.3
		Final	BDL	BDL	BDL	BDL	BDL	210	12.5
	Site 2	Initial	0.024	3.2	0.057	0.68	3.96	17	11.0
Plattsburgh	Fire Training Areas 2 and 3	Initial	BDL	0.026	0.0042	0.14	0.17	5,200	3.8
		Final	BDL	BDL	0.94	1.5	2.4	5,200	10.5
	Fire Training Pit 4	Initial	0.85	0.85	16	80	97.70	4,500	8.3
	Fire Training Area 1	Initial	1.8	30	20	135	186.80	2,500	8.2
Pope	Site ST-08	Initial	BDL	BDL	BDL	BDL	BDL	3,200	12.9
Randolph	Tank 20 Site	Initial	BDL	4.7	3.3	33	41.00	230	10.5
		Final	NS	NS	NS	NS	NS	NS	NS
Robins	UST 173	Initial	BDL	0.00067	0.11	1.0	1.11	1,900	14.3
		Final	BDL	BDL	0.82	0.73	1.6	340	11.2
	SS10	Initial	0.018	20	14	76	110.02	3,100	9.9
		Final	7.3	21	21	100	150	3,600	12.0
Shaw	Site FT-01	Initial	0.31	1.7	3.6	3.2	8.81	4,500	10.2
	Site SS-15	Initial	1.7	3.8	7.1	36	48.60	2,400	11.0
Tinker	POL Storage Area C	Initial	1.9	45	53	83	138.59	2,300	9.4
		Final	0.0012	0.0015	0.0049	0.037	0.045	BDL	11
Travis	Fuel Storage Area G	Initial	0.26	0.69	9.1	13	22.72	64	15.2
		Final	BDL	BDL	13	88	100	5,400	14.6
	South Gas Station	Initial	4.6	22	13	71	110.60	20	17.3
Vandenburg	Service Station	Initial	BDL	5.4	4.9	46	56.30	230	16.6
	JP-4 Site	Initial	0.44	2.0	1.8	6.4	11	6.2	13.1
Westover	Building 7701	Initial	BDL	BDL	BDL	BDL	BDL	BDL	4.7
		Final	BDL	BDL	BDL	BDL	BDL	BDL	NR
	Building 7705	Initial	BDL	0.47	BDL	0.73	1.22	22	9.8
		Final	BDL	0.20	0.087	0.35	0.64	BDL	8.9
Wright Patterson	Fire Training Area	Initial	BDL	0.026	0.0028	0.015	0.04	19.5	19.0
		Final	BDL	BDL	BDL	BDL	BDL	BDL	17.0
	Spill Sites 2 and 3	Initial	BDL	0.016	BDL	0.0054	0.02	BDL	6.6
		Final	BDL	BDL	BDL	BDL	BDL	BDL	4.2

BDL = below detection limit.
NR = not reported
NS = not sampled.

Table B-3. Preliminary Bioventing Initiative Results: BTEX and TPH Soil Gas Concentrations

			Soil Gas Analysis					
Air Force Base	Site	Time	Benzene (ppmv)	Toluene (ppmv)	Ethylbenzene (ppmv)	Total Xylenes (ppmv)	Total BTEX (ppmv)	TPH (ppmv)
AFP 4	FSA-1	Initial	BDL	BDL	21	19	40.96	25,000
		Final	0.24	0.094	0.23	0.67	1.2	290
	FSA-3	Initial	BDL	BDL	6.4	12.5	19.03	12,800
		Final	0.28	0.21	0.65	0.93	2.1	480
AFP PJKS	ST-35	Initial	8.2	8.8	6.5	14	37.50	2,300
		Final	BDL	0.004	0.026	0.070	0.10	11
Battle Creek	Fire Training Area	Initial	50	18	2.8	11	81.40	10,900
		Final	BDL	0.0027	BDL	BDL	0.0027	7.9
Beale	Site 3	Initial	2.3	1.9	0.71	2.3	3.74	3,000
		Final	0.27	0.60	0.87	2.0	3.7	270
	Site 18	Initial	11	1.6	2.0	1.8	16.40	3,600
		Final	4.7	BDL	0.80	1.7	7.2	1,600
	Site 11	Initial	350	530	37	300	1,215.00	59,300
		Final	1.3	13	7.3	180	200	2,800
Bolling	Building 18	Initial	0.056	0.18	0.30	0.74	1.28	317
		Final	BDL	0.0033	0.016	0.058	0.077	15
	Former Storage Tank Farm	Initial	0.21	7.9	4.0	5.2	17.31	11,900
		Final	BDL	BDL	BDL	BDL	BDL	12,700
Camp Pendleton	Site 13115	Initial	0.34	1.2	1.2	3.4	6.1	460
Cannon	SWMU 70	Initial	30	18	7.4	23	78	9,000
Cape Canaveral	FTA-2	Initial	1.5	0.11	3.6	4.8	10.01	3,900
		Final	0.016	0.011	0.026	0.071	0.12	210
	Facility 1748	Initial	1.5	0.021	3.4	3.3	8.22	750
	Facility 44625D	Initial	0.36	0.20	0.015	1.6	2.18	397
	Facility 44625E	Initial	0.059	0.53	0.33	2.2	3.12	303
Charleston	FT-03	Initial	BDL	BDL	0.061	0.11	0.17	410
		Final	BDL	BDL	0.0013	BDL	0.0013	6.7
	ST-27	Initial	126	557	81	253	1,017.00	118,333
	Site SS-41	Initial	0.30	0.30	4.87	9.8	15.27	19,667
Davis Monthan	Site 35	Initial	693	681	93	153	1,620.00	46,098
	Site 36	Initial	583	665	118	254	1,620.00	39,667
Dover	ST-04	Initial	65	44	13.4	47	169.40	33,500
	North STF	Initial	5.4	4.8	2.5	5.4	61.30	6,150
Dyess	Site FT40	Initial	0.015	0.08	0.011	0.042	0.15	49
		Final	BDL	0.002	BDL	0.012	0.014	1.5
	Site FT41	Initial	0.016	0.19	0.14	0.26	0.61	320
		Final	BDL	0.018	BDL	0.013	0.031	1.6
Edwards	Site 21	Initial	190	16	12	38	253.00	49,000
		Final	0.26	0.24	0.72	1.7	2.9	220
	Site 16	Initial	230	26	20	89	365.00	63,000
		Final	0.8	0.83	2	5.3	8.9	575
	Site 43	Initial	BDL	0.0088	0.091	0.48	0.59	380
		Final	BDL	0.006	0.012	0.11	0.13	0.95
Eglin	FTA Hurlebert Field	Initial	36	46	12	78	172.00	17,667
	Old Eglin FTA	Initial	146	179	29	120	474.00	16,000
Eielson	ST-10	Initial	567	150	4.0	43	764.00	48,000
		Final	BDL	1.6	BDL	4.4	6.0	2,100
	Site 48-E2	Initial	66	51	3.4	12	132.40	6,000
		Final	0.32	2.1	2.5	26	31	1,200
	Site 48-E3	Initial	4.6	0.25	0.45	1.1	6.40	1,866
		Final	BDL	BDL	1.8	4.2	6.0	610
Ellsworth	Area D Bulk Fuel Storage	Initial	140	13	12.9	30	128.50	35,000
		Final	0.0091	0.017	2	8.4	10	780
	Building 102 Base Fuel Station	Initial	320	48	6.7	39	416.70	79,000
		Final	BDL	0.074	6.7	32	39	840
Elmendorf	43/45 Valve Pit	Initial	13	80	7.5	28	128.50	13,550

Table B-3. Preliminary Bioventing Initiative Results: BTEX and TPH Soil Gas Concentrations (Continued)

Air Force Base	Site	Time	Soil Gas Analysis Benzene (ppmv)	Toluene (ppmv)	Ethylbenzene (ppmv)	Total Xylenes (ppmv)	Total BTEX (ppmv)	TPH (ppmv)
	ST-61	Initial	0.053	0.32	0.4	1.1	1.87	1,000
		Final	BDL	0.22	0.95	1.3	2.5	200
	ST-71	Initial	BDL	BDL	0.22	1.12	1.35	390
		Final	BDL	0.004	0.032	0.033	0.069	3.2
	43/55 Pumphouse	Initial	19	64	15	50	150	19,700
		Final	0.87	0.86	5.1	33	40	2,700
FE Warren	Fire Training Pit	Initial	0.92	2.5	1.9	5.1	10.42	1,059
	Spill Site	Initial	180	28	24	110	348.00	15,400
		Final	BDL	0.012	0.049	0.27	0.33	33
Fort Drum	Area 1595	Initial	BDL	7.2	2.7	16	26	2,300
Galena	Saddle Tank Farm	Initial	40	8.3	2.7	6.4	57.40	2,745
	Power Plant	Initial	0.059	1.1	3.8	3.5	8.5	897
		Final	0.060	BDL	1.4	3.2	4.7	390
	Million Gallon Hill	Initial	6.4	5.7	0.64	2.5	15	2,000
		Final	BDL	BDL	3.5	10	14	1,000
	Campion POL Leak Site	Initial	0.022	0.040	0.054	0.22	0.34	254
Hanscom	Building 1639	Initial	8.1	10	3.6	17	38.70	7,000
		Final	8.3	9	0.47	5.5	23	1,900
	Building 1812	Initial	NS	NS	NS	NS	NS	NS
Hickam	Area H	Initial	BDL	BDL	28	22	56.80	240,000
		Final	BDL	BDL	0.0067	0.0053	0.012	73
	Area K	Initial	85	BDL	22	48	155.70	26,300
		Final	BDL	BDL	2	5.3	7.3	15,900
	Site 2 FSA	Initial	16	29	12	40	97.00	13,800
		Final	BDL	BDL	7.4	18	25	6,400
Hill	Site 204.1	Initial	0.026	0.11	0.085	0.39	0.61	220
		Final	0.0025	0.0047	BDL	0.0023	0.0095	3.2
	Site 214.1	Initial	0.010	0.039	0.26	0.26	0.57	480
		Final	BDL	BDL	0.036	0.18	0.22	620
	Site 228	Initial	0.81	2.2	0.85	4.7	8.48	1,300
		Final	0.021	0.029	0.016	0.13	0.20	20
	Site 924	Initial	34	80	3.6	34	150	2,900
		Final	0.0025	0.0045	BDL	BDL	0.0070	1.5
	Site 1705	Initial	0.012	0.019	0.011	0.053	0.10	44
		Final	BDL	0.0025	0.0017	0.035	0.039	1.2
	Site 388	Initial	175	180	8.9	80	440.90	26,000
		Final	2.3	97	25	260	380	9,000
	Site 40002	Initial	BDL	280	12	110	303.59	11,100
		Final	1.2	140	9.7	150	300	7,800
	Site 510.8	Initial	BDL	0.18	0.06	0.43	0.69	660
		Final	BDL	BDL	0.065	0.20	0.27	340
Johnston Atoll	Old Fire Training Area	Initial	0.016	0.47	0.95	2.8	4.24	450
	Former POL Tank Farm	Initial	0.1	0.11	3.03	2.3	5.54	3,833
	Storage Tanks 260 and 261	Initial	0.059	0.066	1.5	2.0	3.63	1,588
Keesler	SWMU 66	Initial	23	44	4.5	20	91.50	8,183
	AOC A	Initial	1,100	550	51	120	1,800	130,000
		Final	42	220	53	230	550	22,300
Kelly	Site S-4	Initial	200	22	22	19	265.00	36,500
		Final	0.041	0.88	0.3	0.63	1.9	430
	Site FC-2	Initial	38	15	18	15	86.00	12,400
		Final	BDL	0.6	0.15	0.34	1.1	100
	Site B-2093	Initial	175	323	25	87	610.00	9,467
	Site D-10	Initial	0.003	0.051	0.18	0.34	0.57	54
		Final	BDL	0.016	0.003	0.015	0.034	1.1

Table B-3. Preliminary Bioventing Initiative Results: BTEX and TPH Soil Gas Concentrations (Continued)

			Soil Gas Analysis					
Air Force Base	Site	Time	Benzene (ppmv)	Toluene (ppmv)	Ethylbenzene (ppmv)	Total Xylenes (ppmv)	Total BTEX (ppmv)	TPH (ppmv)
Kirtland	Fire Training Area 13	Initial	19	56	8.3	34	117.30	13,000
		Final	0.011	BDL	0.1	0.56	0.67	690
	Fire Training Area 14	Initial	NS	NS	NS	NS	NS	NS
K.I. Sawyer	POL Area	Initial	393	178	9.1	15	595.10	41,067
	FTA-06	Initial	8.6	7.2	0.53	2.6	19	1,300
		Final	0.16	0.13	0.23	0.68	1.2	20
	FTA-07	Initial	3.1	6.2	0.40	2.2	12	820
		Final	1.2	10	4.0	22	37	710
Little Rock	Fire Training Site 1	Initial	NS	NS	NS	NS	NS	NS
	Spill Site 18	Initial	BDL	BDL	8.7	16	25	23,700
Los Angeles	Building 125	Initial	0.026	0.026	0.089	0.2	0.34	2,200
	Building 241	Initial	0.065	0.31	0.59	0.91	1.88	340
	Gate 3	Initial	0.026	0.026	0.57	1.17	1.79	857
Malmstrom	Pumphouse 2	Initial	6.6	BDL	9.1	12	28	8,800
		Final	BDL	BDL	0.15	0.28	0.43	65
	Bulk POL	Initial	BDL	12	12	38	62	46,000
		Final	BDL	BDL	2	4.2	6.2	580
March	IRP Site 35c	Initial	0.035	0.035	0.41	0.67	1.15	136
McClellan	Building 720	Initial	NS	NS	NS	NS	NS	NS
	Davis Site	Initial	0.0053	0.004	0.39	0.67	1.07	245
		Final	BDL	0.0045	0.0050	0.10	0.11	230
	PRL T-46	Initial	0.18	0.18	3.3	1.84	5.50	7,167
		Final	0.34	3.0	2.8	6.0	12	930
	Study Area 6	Initial	165	124	13	81	383.00	39,264
		Final	3.8	7.2	4.8	36	52	900
	Tank Farm #2	Initial	0.68	28	7.9	30	66.58	29,333
		Final	BDL	0.38	7.0	13	20	11,900
	Tank Farm #4	Initial	0.11	0.11	5.3	5.7	11.22	2,370
		Final	BDL	BDL	0.046	0.15	0.20	27
McGuire	Bulk Fuel Storage	Initial	73	190	17	58	340	54,000
		Final	10	22	5.1	45	82	4,900
Mt. Home	POL Yard	Initial	550	25	560	270	1,400	67,000
Nellis	Site 27	Initial	543	372	37	100	1,052.00	81,667
		Final	6.0	14	5.1	16	41	1,400
	Site 28	Initial	520	547	55	185	1,307.00	72,000
	Site 44	Initial	203	753	68	377	1,401.00	29,333
Newark	Facility 27	Initial	0.019	0.023	0.0097	0.11	0.16	1,043
	Facility 89	Initial	0.0072	0.015	0.0045	0.0088	0.04	28
	Facility 14	Initial	NS	NS	NS	NS	0.00	NS
Offutt	Low Point Drain	Initial	88	153	29	77	347.00	29,750
	Building 30	Initial	BDL	BDL	BDL	1.4	311.00	8,200
		Final	BDL	BDL	BDL	BDL	BDL	170
	Building 406	Initial	290	BDL	44	51	382.92	18,300
		Final	BDL	BDL	6.5	28	35	2,300
	POL Storage Area	Initial	67	11	4	9.5	304.00	13,500
		Final	BDL	BDL	BDL	0.36	0.36	860
Patrick	FTA-2	Initial	BDL	BDL	1.5	5.2	267.60	10,400
		Final	0.048	0.003	0.024	0.058	0.13	68
	BX Service Station	Initial	BDL	44	24	200	7.18	62,000
		Final	0.027	0.002	0.0045	0.23	0.26	4.3
Pease	Bulk Fuel Storage Area	Initial	117	9.7	18	22	166.70	48,000
Plattsburgh	Fire Training Pits 2 and 3	Initial	4.4	10	2.1	14	30.50	4,312
		Final	BDL	0.016	0.0045	0.013	0.034	9.9
	Fire Training Pit 4	Initial	11	18	24	82	140	7,200
	Fire Training Area 1	Initial	6.01	20	4.2	15	45.21	8,348

Table B-3. Preliminary Bioventing Initiative Results: BTEX and TPH Soil Gas Concentrations (Continued)

			Soil Gas Analysis					
Air Force Base	Site	Time	Benzene (ppmv)	Toluene (ppmv)	Ethylbenzene (ppmv)	Total Xylenes (ppmv)	Total BTEX (ppmv)	TPH (ppmv)
Pope	Site ST-08	Initial	BDL	25	4.0	10	39	3,800
Randolph	Tank 20 Site	Initial	16	0.53	6.1	18	40.63	19,667
		Final	BDL	BDL	0.048	0.21	0.26	50
Robins	UST 173	Initial	0.0013	0.028	0.17	1.04	1.24	206
		Final	0.086	0.011	BDL	0.016	0.11	1.1
	SS10	Initial	270	109	16	84	479.00	55,000
		Final	57	40	15	67	180	13,000
Shaw	Site SS-15	Initial	210	200	32	120	560	69,700
Tinker	POL Storage Area C	Initial	53	100	11	36	202.00	11,500
		Final	0.018	0.022	0.73	1	1.8	190
Travis	Fuel Storage Area G	Initial	1,300	550	100	97	2,048.00	110,000
		Final	7.1	11	6.4	31	56	2,300
	South Gas Station	Initial	1,650	1,125	61	240	3,076.00	145,000
Vandenburg	Service Station	Initial	160	84	28	139	411.00	19,467
	JP-4 Site	Initial	NS	NS	NS	NS	NS	NS
Westover	Building 7701	Initial	NS	NS	NS	NS	NS	NS
		Final	610	BDL	0.13	0.031	610	0.57
	Building 7705	Initial	BDL	BDL	0.12	0.087	0.23	92
		Final	BDL	0.0093	0.0063	0.023	0.039	0.34
Wright Patterson	Fire Training Area	Initial	0.23	0.42	0.21	0.29	1.15	1,147
	Spill Sites 2 and 3	Initial	0.07	2.59	1.92	6.76	11.34	2,398

NS = not sampled.
BDL = below detection limit.

Table B-4. In Situ Respiration Test Results at Bioventing Initiative Sites

		Initial		6-Month		1-Year	
Air Force Base	**Site**	**%/hr**	**mg/kg-day**	**%/hr**	**mg/kg-day**	**%/hr**	**mg/kg-day**
AFP 4	FSA-1	0.32	5.22	0.058	0.95	0.059	0.96
	FSA-3	0.91	14.85	0.36	5.88	0.54	8.81
AFP PJKS	ST-35	0.52	8.49	0.17	2.77	0.33	5.39
Battle Creek	Fire Training Area	0.39	6.36	0.12	1.96	0.16	2.61
Beale	Site 3	0.14	2.28	0.043	0.70	0.016	0.26
	Site 18	0.74	12.08	0.078	1.27	0.069	1.13
	Site 11	0.12	1.96	0.031	0.51	0.033	0.54
Bolling	Building 18	0.11	1.80	0.011	0.18	0.080	1.31
	Former Storage Tank Farm	1.4	22.85	1.5	24.48	0.98	15.99
Camp Pendleton	Site 1	0.021	0.34	NC	NC	NC	NC
Cannon	SWMU 70	0.53	8.65	NC	NC	NC	NC
Cape Canaveral	FTA-2	0.18	2.94	NC	NC	NC	NC
	Facility 1748	0.16	2.61	NC	NC	NC	NC
	Facility 44625D	0.39	6.36	NC	NC	NC	NC
	Facility 44625E	0.17	2.77	NC	NC	NC	NC
Charleston	FT-03	0.54	8.81	0.0059	0.10	0.084	1.37
	Site SS-41	0.38	6.20	NC	NC	NC	NC
Davis Monthan	Site 35	0.009	0.15	NC	NC	NC	NC
	Site 36	0.078	1.27	NC	NC	NC	NC
Dover	ST-04	0.18	2.94	NC	NC	NC	NC
	North STF	0.30	4.90	NC	NC	NC	NC
Dyess	Site FT40	0.010	0.16	NC	NC	NC	NC
	Site FT41	NC	NC	NC	NC	NC	NC
Edwards	Site 21	0.16	2.61	0.016	0.26	0.23	3.75
	Site 16	0.031	0.51	0.0051	0.08	0.059	0.96
	Site 43	0.033	0.54	0.0060	0.10	0.019	0.31
Eglin	FTA Hurleburt Field	0.18	2.94	NC	NC	NC	NC
	Old Eglin FTA	0.18	2.94	NC	NC	NC	NC
Eielson	ST-10	0.29	4.73	0.22	3.59	0.10	1.63
	Site 48-E2	0.18	2.94	0.046	0.75	0.11	1.80
	Site 48-E3	NC	NC	0.067	1.09	0.11	1.80
Ellsworth	Area D Bulk Fuel Storage	1.1	17.95	0.068	1.11	0.074	1.21
	Building 102 Base Fuel Station	0.034	0.55	0.0096	0.16	0.0056	0.09
Elmendorf	43/45 Pumphouse	0.51	8.32	0.09	1.47	0.32	5.22
	ST-61	0.38	6.20	0.072	1.18	0.44	7.89
	ST-71	0.056	0.91	0.015	0.24	0.06	1.23
	43/55 Pumphouse	0.34	5.55	0.0066	0.11	0.16	2.61
FE Warren	Fire Training Pit	0.62	10.12	NC	NC	NC	NC
	Spill Site	1.4	22.85	0.052	0.85	0.018	0.29
Galena	Saddle Tank Farm	1.05	17.14	NC	NC	NC	NC
	Power Plant	1.4	22.85	NC	NC	0.059	9.63
	Million Gallon Hill	0.44	7.18	NC	NC	0.11	1.80
	Campion POL Leak Site	0.99	16.16	NC	NC	NC	NC
Hanscom	Building 1639	0.78	12.73	0.26	4.24	0.048	0.78
	Building 1812	NC	NC	0.036	0.59	NC	NC

Table B-4. In Situ Respiration Test Results at Bioventing Initiative Sites (Continued)

		Initial		6-Month		1-Year	
Air Force Base	**Site**	**%/hr**	**mg/kg-day**	**%/hr**	**mg/kg-day**	**%/hr**	**mg/kg-day**
Hickam	Area H	0.71	11.59	0.093	1.52	0.012	0.20
	Area K	1.2	19.58	0.45	7.34	0.38	6.20
	Site 2 FSA	0.6	9.79	0.27	4.41	0.53	8.65
Hill	Site 204.1	0.98	15.99	0.057	0.93	0.096	1.57
	Site 214.1	0.31	5.06	0.015	0.24	0.015	0.24
	Site 228	0.54	8.81	0.031	0.51	0.059	0.96
	Site 924	0.56	9.14	0.043	0.70	0.007	0.12
	Site 1705	NC	NC	NC	NC	NC	NC
	Site 388	0.42	6.85	0.090	1.47	0.39	6.36
	Site 40002	0.22	3.59	0.016	0.26	0.083	1.35
	Site 510.8	0.022	0.36	0.021	0.34	0.091	1.49
Johnston Atoll	Old Fire Training Area	0.42	6.85	NC	NC	0.44	7.2
	Former POL Tank Farm	0.24	3.92	NC	NC	0.22	3.5
	Storage Tanks 260 and 261	0.64	10.44	NC	NC	0.23	3.7
Keesler	SWMU 66	0.65	10.61	0.41	6.69	0.60	9.79
	AOC A	0.081	1.32	0.097	1.58	0.083	1.35
Kelly	Site S-4	2.4	39.17	0.28	4.57	0.11	1.80
	Site FC-2	1.9	31.01	0.72	11.75	0.58	9.47
	Site D-10	1.1	17.95	0.057	0.93	0.070	1.14
Kirtland	Fire Training Area 13	0.061	1.00	0.012	0.20	0.0083	0.13
	Fire Training Area 14	0.0055	0.09	0.0043	0.07	NC	NC
KI Sawyer	POL Area	0.11	1.80	0.11	1.80	0.16	2.61
	FTA-06	0.13	2.12	0.047	0.77	0.029	0.47
	FTA-07	0.074	1.21	0.021	0.34	0.012	0.20
Little Rock	Spill Site 18	2.04	33.29	NC	NC	NC	NC
Los Angeles	Building 125	0.33	5.39	NC	NC	NC	NC
	Building 241	0.25	4.08	NC	NC	NC	NC
	Gate 3	0.27	4.41	NC	NC	NC	NC
Malmstrom	Pumphouse II	3.2	52.22	0.29	4.73	NC	NC
	POL SA	1.1	17.95	0.34	5.55	0.25	4.08
March	IRP Site 35c	0.29	4.73	NC	NC	NC	NC
McClellan	Davis Site	0.37	6.04	0.12	1.96	0.50	8.16
	PRL T-46	0.91	14.85	0.19	3.10	0.37	6.04
	Study Area 6	0.32	5.22	0.016	0.26	0.11	1.80
	Tank Farm #2	0.31	5.06	0.030	0.49	0.064	1.04
	Tank Farm #4	0.33	5.39	0.011	0.18	0.099	1.62
McGuire	Bulk Fuel Storage	1.2	19.58	0.28	4.57	0.72	11.75
Mt. Home	POL Yard	0.32	5.22	NC	NC	NC	NC
Nellis	Site 27	0.048	0.78	0.0035	0.06	0.031	0.51
	Site 28	0.21	3.43	0.038	0.62	0.016	0.26
	Site 44	0.69	11.26	0.028	0.46	0.022	0.36
Newark	Facility 27	0.026	4.24	NC	NC	0.015	0.24
	Facility 89	0.021	0.34	0.0096	0.16	0.021	0.34
Offutt	Low Point Drain	0.86	14.04	NC	NC	NC	NC
	Building 406	5.6	91.39	0.33	5.39	0.26	4.24
	Building 30	4.9	79.97	0.051	0.83	0.039	0.64
	POL Storage Area	0.1	1.63	NC	NC	0.46	7.51

Table B-4. In Situ Respiration Test Results at Bioventing Initiative Sites (Continued)

		Initial		6-Month		1-Year	
Air Force Base	**Site**	**%/hr**	**mg/kg-day**	**%/hr**	**mg/kg-day**	**%/hr**	**mg/kg-day**
Patrick	FTA-2	0.34	5.55	0.41	6.69	0.33	5.39
	BX Service Station	0.16	2.61	0.21	3.43	0.028	0.46
Pease	Bulk Fuel Storage Area	3.57	58.26	NC	NC	NC	NC
Plattsburgh	Fire Training Areas 2 and 3	0.84	13.71	0.17	2.77	0.094	1.53
	Fire Training Pit 4	0.20	3.26	NC	NC	NC	NC
Randolph	Tank 20 Site	0.41	6.69	0.15	2.45	0.28	4.57
Robins	UST 173	0.029	0.47	0.0023	0.04	0.013	0.21
	SS10	0.18	2.94	0.031	0.51	0.020	0.33
Shaw	Site FT-01	0.43	7.02	NC	NC	NC	NC
	Site SS-15	0.16	2.61	NC	NC	NC	NC
Tinker	POL Storage Area C	0.18	2.94	0.038	0.62	0.056	0.91
Travis	Fuel Storage Area G	3.6	58.75	0.79	12.89	0.86	14.04
	South Gas Station	2.47	40.31	NC	NC	NC	NC
Vandenburg	Service Station	0.24	3.92	NC	NC	NC	NC
Westover	Building 7701	0.33	5.39	0.0098	0.16	0.052	0.85
	Building 7705	0.12	1.96	NC	NC	0.05	0.82
Wright Patterson	Fire Training Area	0.19	3.10	NC	NC	NC	NC
	Spill Sites 2 and 3	0.26	4.24	NC	NC	NC	NC

NC = not conducted.