A GENERAL EVALUATION OF BIOVENTING
for
REMOVAL ACTIONS
at
AIR FORCE / DEPARTMENT OF DEFENSE INSTALLATIONS
NATIONWIDE

General Engineering Evaluation /
Cost Analysis (EE/CA)

JUNE 1996

Air Force Center for Environmental Excellence (AFCEE)
Technology Transfer Division
Brooks Air Force Base, San Antonio, Texas

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General Engineering Evaluation / Cost Analysis (EE/CA)

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June 1996

ACKNOWLEDGEMENTS

The authors would like to thank all of the personnel that contributed to the success of the Air Force Center for Environmental Excellence (AFCEE) Bioventing Initiative Project. Included are the professional staff of AFCEE and of the many Air Force bases, and the research consultants Parsons Engineering Science, Inc. and Battelle Memorial Institute. A special thanks goes to Brian Blicker and Craig Snyder of Parsons Engineering Science, Inc. in Denver, Colorado, who compiled much of the site-specific information contained in this report.

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Section 1
INTRODUCTION

This Engineering Evaluation/Cost Analysis (EE/CA) document supports bioventing as the preferred alternative for non-time-critical removal action to remediate fuel-hydrocarbon contamination in soils at Air Force installations nationwide. The National Contingency Plan (NCP) requires the lead agency to conduct an EE/CA or its equivalent for non-time-critical removal actions (USGPO, 1990 - 40 CFR 300.415). The EE/CA process is a comparative analysis of removal action alternatives and is recorded in the EE/CA document for public review and comment.

A conventional EE/CA document generally supports a decision to take a removal action at a specified site or group of sites. This document is a modified EE/CA, a General Evaluation Document, designed to facilitate decision making and to streamline the administrative process in the Air Force Installation Restoration Program (IRP). This is accomplished by focusing on the general applicability of a single technology (bioventing in this case) rather than on a single site. This General Evaluation Document establishes a site-selection methodology that defines site conditions requiring early action and to effective bioventing application.

Site-Specific Documents will be written as needed to demonstrate that bioventing should be applied in specific cases. At present, there are numerous sites on Air Force installations nationwide where bioventing is feasible, and additional sites are expected to be identified in the future as site investigation and evaluation continues. Bioventing will clearly play a significant role in achieving the Air Force's goal of initiating cost-effective cleanup at all fuel-hydrocarbon-contaminated sites by the year 2000.

Presumptive Remedy and Plug-In Approaches

The efficient application of basewide bioventing removal actions at Air Force installations nationwide relies on two parallel approaches:

- The ***presumptive remedy approach*** allows the Air Force to rapidly select a technology that has repeatedly been proven effective under particular site conditions (in this case, bioventing).
- The ***plug-in approach*** allows the Air Force to rapidly identify sites that are suitable for bioventing removal action.

Presumptive Remedy Approach

The term "presumptive remedy" refers to a remedial technology that has been consistently selected as the preferred remedial technology through the remedy selection process, or is a remedial technology that is known to be effective at sites with similar characteristics as the site in question. The US Environmental Protection Agency (EPA) has embraced the development of presumptive remedies as one element of its ongoing effort to standardize and streamline the remedy selection process (USEPA, 1991a). Therefore, the presumptive remedy approach allows the Air Force to select bioventing as the preferred technology by demonstrating that bioventing is effective under similar site conditions.

The presumptive remedy approach consists of the following philosophy:

*At times site conditions are so well suited to a particular technology that the technology can be **presumed** to be appropriate without an exhaustive evaluation. This approach allows the selection of a remedial technology which has been repeatedly shown to work within the range of conditions present at the site.*

Section 2 of this General Evaluation Document summarizes the state-of-the-art of the bioventing technology. Section 3 of this document contains a basis of rejecting non-bioventing alternative technologies and a basis for selecting bioventing based on its advantages over the other alternatives. Section 4 summarizes numerous studies supporting bioventing as a remediation technology for fuel-hydrocarbon contamination in vadose-zone soils at Air Force installations. These discussions collectively form the preponderance of evidence supporting the selection of bioventing as a presumptive remedy for removal of fuel hydrocarbons from soils.

Plug-In Approach

The plug-in approach allows the Air Force and the regulatory agencies to evaluate sites rapidly to determine their suitability for the application of bioventing as a removal action. This approach can be used when an Air Force installation contains multiple areas or sites that have similar physical characteristics and contain similar contaminants (USEPA, 1993a; USEPA, 1993b). A site-selection methodology has been developed for bioventing removal actions at Air Force installations (Section 6). The plug-in process for bioventing removal actions requires the evaluation of both bioventing feasibility and the need for removal action.

The "plug-in" approach consists of the following steps:

- *The identification of a remedy-specific response action*
- *The development of a selection methodology that outlines the process to evaluate both technical feasibility and the need for response action*
- *The use of the selection methodology to identify sites that can "plug-in" the selected action*

When making decisions about bioventing removal actions, the Air Force does not have to conduct a full-scale conventional EE/CA for each proposed site. If site conditions match those specified in the site-selection methodology, the standard process for remedy evaluation and analysis is not necessary, and the site can "plug in" the bioventing removal action. The decision process and administrative requirements for such sites will be streamlined by referencing this General Evaluation Document. Sites that do not pass the site evaluation will not "plug in" the bioventing removal action, but will be addressed by a separate response action or remedy.

Framework for Nationwide Bioventing Removal Actions: Superfund Accelerated Cleanup Model

The Superfund Accelerated Cleanup Model (SACM) is the new model developed by EPA to streamline the Superfund program and to be more responsive to the public's needs. Under this new approach, the distinctions between removal and remedial actions are eliminated. All sites will undergo one site assessment that combines appropriate elements from the current preliminary assessment/site investigation

(PA/SI), remedial investigation/feasibility (RI/FS), and risk assessment. During the assessment process, early short-term actions will be taken to reduce the majority of risk to human health and the environment. These short-term actions include cleanup activities generally taking no more than five years.

With the application of SACM to federal facilities has not yet been fully developed, the Air Force has incorporated the main thrust of SACM and has focused base remedial programs on early actions to reduce risk. It is expected these early actions will be taken through the currently available response mechanisms, including both non-time-critical removal actions and interim remedial actions. To gain the most leverage from these actions, factors such as the magnitude and the imminence of the risk posed by sites will be considered in selecting sites for early action.

The Air Force has selected several sites that are suitable for early action using bioventing. The most prevalent pattern of contamination at these sites is high concentrations of fuel hydrocarbons, including aromatic hydrocarbons, in soils extending from the ground surface to the groundwater table in some instances. Bioventing has been demonstrated to be very effective in removing large amounts of fuel hydrocarbons from the soil, and bioventing is generally compatible with other remedial technologies.

The application of bioventing at Air Force installation sites will achieve the short-term goal of reducing risk to human health and the environment in the following ways:

- *Removing large quantities of fuel hydrocarbons, particularly the more mobile and toxic BTEX components, from the soils*
- *Intercepting the exposure pathways*
- *Reducing additional flux of fuel hydrocarbons to the groundwater*

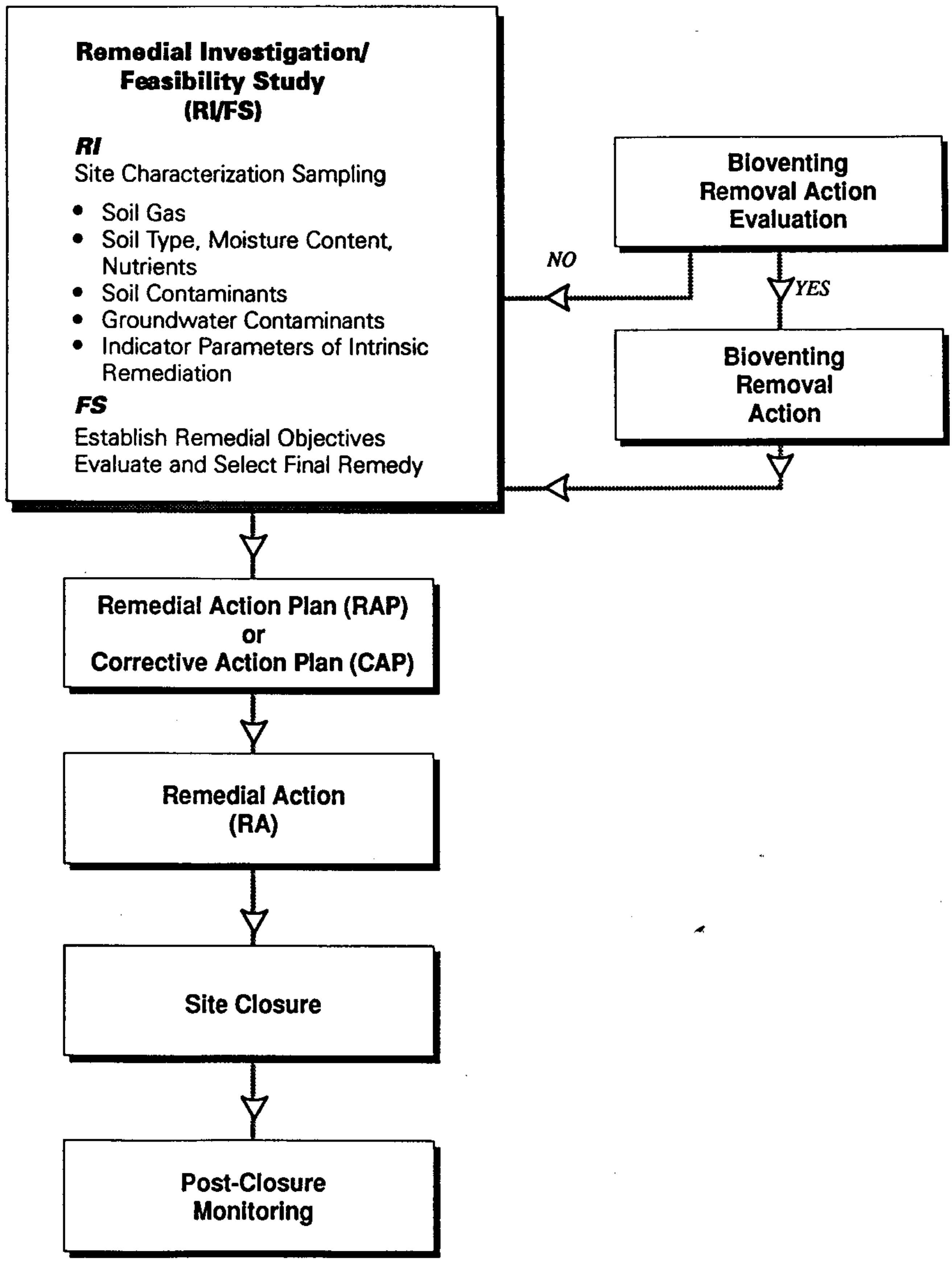
Integration of Bioventing Removal Actions with the Air Force IRP

Figure 1-1 illustrates the role of bioventing removal actions in the Air Force IRP. During the RI phase, field sampling is performed both to identify sources and to define the nature and extent of contamination. At some sites, shallow soil-gas sampling and downhole soil-gas sampling during drilling are used to characterize fuel contamination in soils. The rapid availability of soil-gas measurements allows a quick appraisal of results so that further characterization needs can be determined and remedial decisions can be made.

As soon as soil-gas measurements and soil characteristics are available, a site can be evaluated for the need to take a bioventing removal action before site characterization is complete. If the site is selected for a bioventing removal action, the bulk of fuel hydrocarbons will be removed *in situ* from the site while the remaining RI continues. Following the removal action, the site remedial decision will be evaluated with the additional RI results, taking into account other contamination (e.g., halogenated VOCs, metals in soils, or groundwater contamination) and any residual fuel-hydrocarbon contamination remaining.

FIGURE 1-1

BIOVENTING REMOVAL ACTIONS AND THE AIR FORCE IRP



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Contaminant Cleanup Levels

It is the Air Force's strategy to reach agreement with regulatory agencies on final cleanup levels at the earliest possible opportunity rather than postponing the decisions until the final basewide Remedial Action Plan (RAP) or Corrective Action Plan (CAP) is written. Whenever possible, cleanup levels will be based on risk reduction rather than arbitrary numerical standards. Early determination of cleanup levels is important in deciding whether or not action needs to be taken. It also provides definitive system performance requirements early in the IRP process.

At present, however, the advantages of setting cleanup levels early in the IRP are offset by the disadvantages of applying cleanup levels that are too low to achieve. Of particular concern are certain state non-degradation policies for the protection of groundwater which require cleanup goals equivalent to background concentrations. If such goals are not technically and economically feasible, then the cleanup levels will be set at the lowest level achievable, as supported by information on technical feasibility and cost-effectiveness.

The Air Force approach to facilitate the development of early, yet realistic, cleanup levels:

- *Removal actions will not specify final cleanup levels, but will contribute to the cost-performance information needed*
- *Interim remedial actions will specify final cleanup levels*

Decision Support Documents for Bioventing Removal Action

General Evaluation Document

Bioventing removal actions at Air Force installations are supported by a variant of the standard EE/CA. Traditionally, Corrective Action Plans (CAPs) are focused on a single site or on a group of sites, and each site is considered as a unique problem. As a result, the traditional administrative process requires that a separate, comprehensive EE/CA be prepared for every time-critical removal action. The standard EE/CA includes the following four sections of the remedy selection process:

- Identification of the alternative remedies, based on screening a wide range of alternatives
- Description of the evaluation of each of the identified alternatives
- Summary of the comparative analysis, including the strengths and weaknesses of each alternative relative to others
- Identification of the proposed removal action

The purpose of such a detailed analysis of alternatives is to provide decision makers with adequate information to permit selection of an appropriate remedy. However, the Air Force believes that this conventional approach is not necessary (USEPA, 1993a) and that the remedy selection can be simplified for many reasons:

Justification for implementing bioventing via a General Evaluation Document rather than a standard EE/CA:

- *Many sites at Air Force installations share similar characteristics. Because of these similarities, it is expected that remediation will involve similar approaches, making it possible to develop a selection process that is applicable to several sites at many Air Force installations.*
- *There are few remedial alternatives to bioventing for fuel-hydrocarbons in deep soils, especially fuels such as diesel fuel, waste oils, and heating fuels that are of relatively low volatility.*
- *There is a plethora of information demonstrating the effectiveness of bioventing (AFCEE Bioventing Initiative Project), and decision makers are now familiar with this technology.*

Bioventing removal actions at Air Force installations will be supported by this EE/CA for Bioventing General Evaluation Document, as well as site-specific documents. This General Evaluation Document focuses on generic aspects of representative sites at Air Force installations rather than on site-specific features. The General Evaluation Document outlines a comprehensive plan to standardize and streamline the use of bioventing at Air Force installations. This is accomplished through the development of site-selection methodology, bioventing technology description, and cost estimating methodology, as shown in Figure 1-2.

This General Evaluation Document is intended to be a living document, updated as needed to reflect new information from removal actions at Air Force installations, as well as any other relevant information. Updates will be handled via addenda to this Document.

Site-Specific Documents

Bioventing removal actions for specific sites will be supported by focused, Site-Specific Documents that will reference, but will not repeat, the General Evaluation Document. The Site-Specific Documents will focus on site features that are either different from or absent in the General Evaluation Document. Each Site-Specific Document will contain enough detail to support the Action Memorandum that authorizes a bioventing removal action at a site.

Outline of Site-Specific Documents

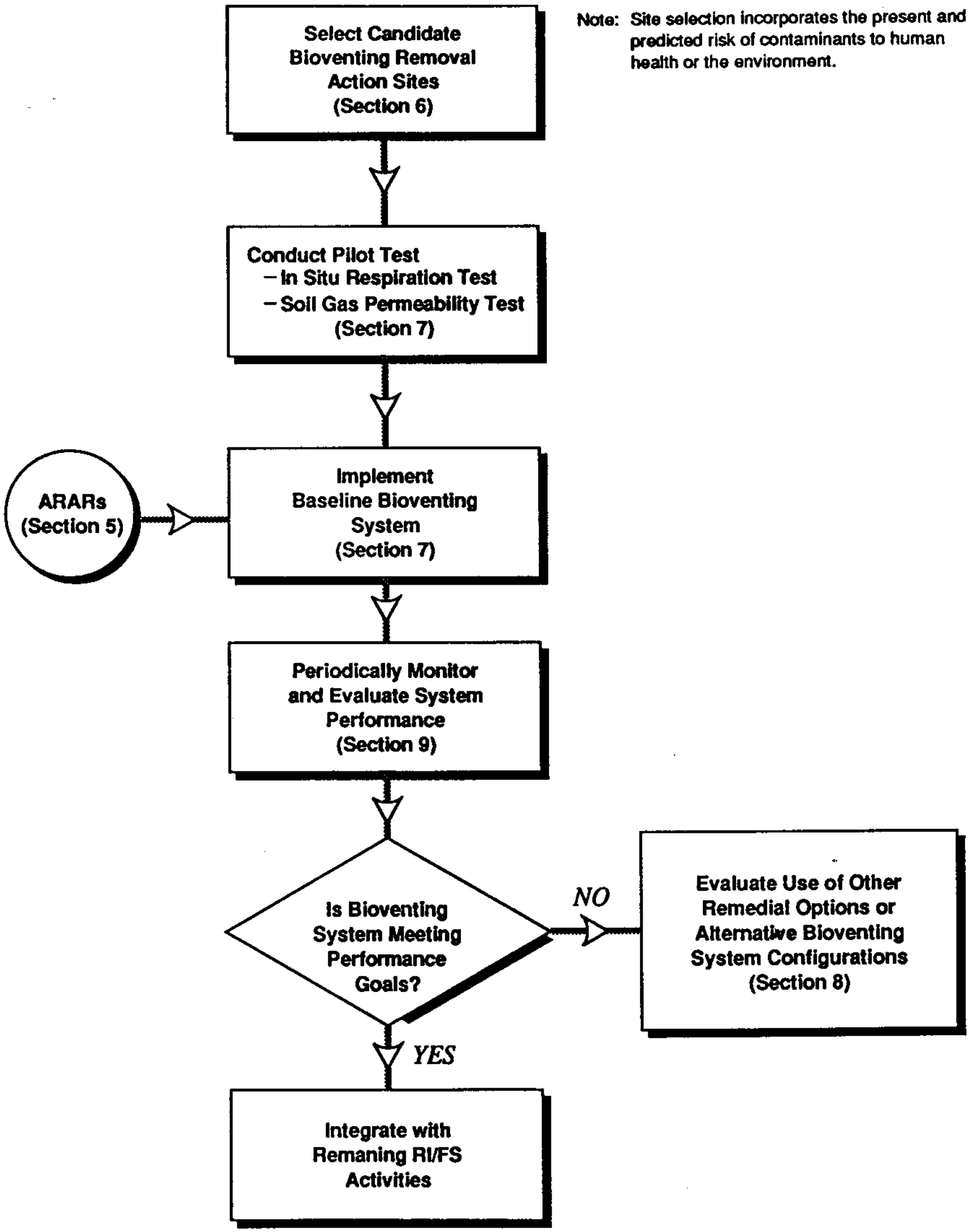
Site-Specific Work Plans

Work plans will be developed for each site where bioventing will be implemented. These work plans will document the overall management and implementation strategy for project activities at each site. The plans will include the responsibilities and authorities of all organizations and key personnel involved. All site-specific aspects will be detailed as appropriate. Each work plan will detail the following areas:

- Requirements for additional field-data collection
- Requirements for system test and optimization
- Requirements for permits and site access agreements
- Schedule for completion of the work
- Analysis and system design criteria
- Health and Safety Plan for the site
- Quality assurance and quality control provisions of site activities

FIGURE 1-2

DECISION FRAMEWORK FOR BIOVENTING SYSTEM IMPLEMENTATION



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Site-Specific Corrective Action Plan (CAP) Documents

Site-specific plans for the practical and effective bioventing system(s) will be prepared to meet the objectives of the removal action. The final report will be prepared in one stage for small (3 or less vent wells) full-scale plans. This one stage will be an intermediate (65%) plan. The final report will be prepared in two stages for large (more than 3 vent wells) full-scale plans. These two stages will be a preliminary (35%) and an intermediate (65%) plan. The complete CAP will be comprised of four distinct parts:

- Plans and specifications
- Cost estimates
- Project schedule
- Operation and Maintenance Plan

Bioventing systems are considered non-complex because equipment used is relatively simple in design and operation. Thus a traditional multiple submittal plan is not typically necessary. Large, multiple-well systems implemented at complex sites may however require a multiple submittal plan.

Plans and Specifications

Clear and comprehensive plans and specifications will be developed and will include the following:

- Discussion of strategy and basis of the plan
- Discussion of important technical factors
- Description of assumptions and their justification
- Discussion of possible sources of error and references to possible operation and maintenance problems
- Discussion of test and optimization of system
- Engineering drawings
- Tables listing equipment and specifications
- Tables detailing material and energy balances
- Appendices including:
    - Data/results of laboratory or field studies
    - Sample calculations and derivation of equations

Cost Estimates

Detailed cost estimates will be developed for construction and implementation of the bioventing removal action, and costs will be broken down into labor, material, and plant costs. Bioventing system life-cycle costs will also be provided for planning and budgeting purposes. These cost estimates will break down the various development costs, construction costs, operation and maintenance costs, and long-term monitoring costs for each fiscal year.

Operation and Maintenance Plans

An Operation and Maintenance (O&M) Plan will be developed for each bioventing system to cover both implementation and long-term maintenance of the bioventing removal action. Each O&M Plan will include the following elements:

- Equipment start-up procedures and specifications
- Description of normal O&M
- Potential operating problems
- Contingency O&M provisions for system failure
- Health and Safety Plan
- Equipment description
- Routine monitoring and laboratory testing procedures

Section 2
DESCRIPTION OF BIOVENTING TECHNOLOGY

General Discussion

Major Features

Bioventing involves aeration of soils to stimulate *in situ* biologic activity and promote biodegradation of fuel-hydrocarbon contaminants. Although there is some evidence that bioventing can enhance the remediation of groundwater by increasing dissolved oxygen (Barr, 1993), bioventing is primarily a soil remediation or source removal technique. The main feature of this technology is that it enhances and accelerates the natural biodegradation process. Naturally-occurring microorganisms degrade the fuel hydrocarbon contaminants by using them as a carbon source for cell production and carbon dioxide production during respiration. Although the soil microorganisms are capable of degrading fuel hydrocarbons under both anaerobic and aerobic conditions, biodegradation rates are generally much faster under aerobic conditions. In fuel-contaminated soil, oxygen is typically depleted because respiration rates exceed rates of oxygen recharge via diffusion. Therefore, venting the contaminated soils with forced air delivers oxygen required to accelerate biodegradation of fuel hydrocarbons. The addition of nutrients or moisture is typically not required, but can be evaluated through site-specific testing and comparison of site-specific nutrient and moisture levels to data collected at other sites.

Bioventing features:

- *Aeration of contaminated soils to stimulate in situ biologic activity for biodegradation of fuel hydrocarbons.*
- *Production/enhancement of the natural biodegradation process.*
- *Low air flow rates used to minimize volatilization.*
- *Air injection implemented to eliminate off-gas production and treatment.*
- *Can be applied to low-volatile fuels such as diesel and heating oil.*
- *Implementation is mechanically simple and requires minimal maintenance.*

Biodegradation vs. Volatilization

The end-products of the biodegradation process are carbon dioxide and water. Aeration of soil causes some volatilization of light fuel hydrocarbons. However, in contrast to soil vapor extraction, bioventing utilizes low air flow rates to provide only enough oxygen to sustain microbial activity and minimize volatilization. Also, because biodegradation is the main remediation mechanism, air injection can often be utilized for venting soils in lieu of soil-gas extraction. Therefore, off-gas treatment can be minimized or eliminated by implementing air injection and air flow rate management. This can reduce remediation costs by 50% or more on sites where vapor emissions must be treated (Miller and Hinchee, 1990a; Reisinger et al., 1993).

Applications

Bioventing has a widespread potential application because soil microorganisms are capable of degrading a wide variety of petroleum products, including gasoline, jet-propulsion fuel, diesel fuel, and heating oils. This technology has a particular advantage in soils contaminated with heavier, less volatile fuels where technologies that depend on lowering soil-gas vapor pressures to induce volatilization such as (i.e., soil vapor extraction) are not as effective.

Physical Processes Affecting Bioventing Success

Four primary physical characteristics that affect bioventing success are:

- *Soil gas permeability*
- *Oxygen diffusion in soil*
- *Contaminant distribution*
- *Radius of oxygen influence*

Soil Gas Permeability

Assuming contaminants are present that are amenable to bioventing, soil gas permeability is generally the most important soil characteristic for the successful application of bioventing. Soils must be sufficiently permeable to allow movement of enough soil gas to provide adequate oxygen for biodegradation, on the order of 0.25 to 0.5 pore volumes per day. Soil gas permeability is a function of both soil structure and particle size, as well as soil moisture content. Typically, permeability in excess of 0.1 darcy is adequate for sufficient air exchange. Below this level, bioventing may be possible, but high-pressure air pumps and long-term field testing may be required to establish feasibility.

Oxygen Diffusion in Soil

When soil gas permeability falls below 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. However, the degree of treatment will be very site specific.

Contaminant Distribution

It is important to have a clear understanding of subsurface contaminant distribution since an air delivery system must be designed to efficiently provide sufficient oxygen to contaminated soils. Many of the sites at which bioventing can be applied are contaminated with immiscible liquids, such a fuel hydrocarbons. The contaminants may be present in any or all of four phases in the geologic media: sorbed phase on soil grains; vapor phase in vadose zone; free-phase (floating on water table or as droplets in vadose zone); and in aqueous phase (dissolved in vadose zone pore water or in groundwater). Dissolved fuel hydrocarbons in the groundwater are considered to be of greatest concern due to the risk of humans being exposed to contaminants through drinking water. However, the free-phase and sorbed-phase hydrocarbons act as feed stocks for groundwater contamination, so any remedial technology aimed at reducing groundwater contamination must address these sources of contamination in the vadose zone.

Radius of Oxygen Influence

An estimate of the oxygen radius of influence 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 can be supplied. This definition 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. The radius of influence is a function of soil properties, but it is also dependent on the configuration of the venting well, extraction or injection flow rates, microbial activity, and the radius of influence is altered by soil stratification.

Principles of Microbial Processes

All principles and parameters that affect microbial processes are important in understanding the actual mechanisms of bioremediation. The major principles are discussed below. However, the emphasis of determining whether site conditions are appropriate for bioventing (discussed in Section 6) is whether or not the microorganisms at a site are sufficiently active. This is evaluated through measuring oxygen-utilization rates via *in situ* respiration (ISR) testing and comparing these rates in both contaminated and clean areas (discussed in Section 7).

Substrate Utilization

As previously discussed, bioventing relies on biological degradation as the main contaminant removal mechanism. 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. To predict the amount of time required for biologic degradation of contaminants, it is necessary to understand the microbial kinetics of substrate utilization. Most substrate utilization is where carbon sources such as the fuel hydrocarbon contaminants supply most of the carbon for growth and energy for the microorganism (this is called primary substrate utilization). Other forms of substrate utilization may explain metabolism of alternative carbon sources, such as in the case of cometabolism. During the process of bioventing, 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 be a mechanism of TCE degradation.

Bioavailability of Contaminants

Bioventing kinetics are complicated by the bioavailability of the contaminants. This factor is a function, at least in part, by solubilization. Although high soil contaminant concentrations may be present, the actual concentration of hydrocarbon dissolved in the pore water and readily available to the microorganisms may be low. This may be reflected when rates of biodegradation slowly decline with time. At many sites, this trend may be difficult to follow over periods of less than one year 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 be due, at least in part, to changes in the hydrocarbon makeup as the more degradable, mobile, soluble, and therefore more bioavailable compounds (i.e., BTEX) are removed.

Environmental Parameters Affecting Microbial Processes

Laboratory studies show that hydrocarbons are biodegradable if the environmental conditions are amenable. Therefore, bioventing is dependent upon providing microorganisms the proper conditions for active growth. Several factors may affect a microorganisms's ability to degrade contaminants, including oxygen levels, moisture content, soil pH, soil temperature, nutrient availability, contaminant concentration, bioavailability, and relative biodegradability. The effects of each of these factors were evaluated under the Bioventing Initiative Project (Section 4). Each of these factors are discussed below.

Oxygen Levels

One of the most important factors which influences the biodegradability of a compound is the amount of available oxygen. Following a fuel spill, anaerobic conditions typically predominate in the subsurface because of oxygen depletion from microbial activity. Fuel hydrocarbons may undergo limited biodegradation under anaerobic conditions (Bilbo et al., 1992; Mormile et al., 1994), however, aerobic conditions are generally more suitable for relatively rapid remediation of fuel hydrocarbons. Therefore, oxygen supply is critical 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 (Miller et al., 1991). This has been confirmed by the Bioventing Initiative Project (Section 4), in which oxygen has been found to be the only factor limiting microbial activity at numerous sites.

Moisture Content

Soil moisture content may impact the bioventing process, since microorganisms require moisture for metabolic processes and for solubilization of energy and nutrient supplies. In addition, soil moisture content directly affects the soil permeability and may contribute to poor distribution of oxygen and nutrients. In practice, soil moisture has been found to limit biodegradation rates only where bioventing has been implemented in very dry desert environments. More frequently, excess moisture has led to soil gas permeability problems. One of the direct objectives of the Bioventing Initiative Project (Section 4) was to assess the effects of moisture on biodegradation.

Soil pH

Soil pH may also affect the bioremediation process, since microorganisms require a specific pH range in order 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 will exhibit optimal growth at a specific pH. Results of the Bioventing Initiative Project (Section 4) show that rarely, if ever, has pH been found to limit *in situ* bioremediation, and is probably only of concern where contamination has radically altered the existing soil pH.

Soil Temperature

Soil temperature may significantly affect the bioremediation process. Microbial activity has been reported at temperatures varying from -12 to 100 °C (10 to 212 °F) (Leeson and Hinchee, 1995); however, the optimal range for biodegradation of most contaminants in soil is generally much narrower. An individual microorganism may tolerate a temperature range of up to approximately 40 °C (104 °F), however, a microorganism's optimal growth temperature may vary depending on the climate. It has been generally observed that biodegradation rates double for every 10 °C (18 °F) temperature increase, up to some inhibitory temperature (Van't Hoff-Arrhenius equation). In extremely cold environments, heat addition may substantially improve bioventing processes. Solar warming, warm water infiltration, and buried heat tape have been used to increase soil temperature. Their use has resulted in increased microbial activity and contaminant degradation at sites near the Arctic Circle (Leeson et al., 1993).

Nutrient Supply

In order to sustain microbial growth, certain nutrients must be available at minimum levels. The following nutrients are known to be required in order to support microbial growth: calcium, cobalt, copper, iron, magnesium, manganese, molybdenum, nitrogen, phosphorous, potassium, sodium, sulfur, and zinc. Nitrogen and phosphorous are required in the greatest concentrations and often are the nutrients that are the most likely to be limiting. The remaining chemicals are considered micronutrients, because they are required in only small quantities and generally are available in excess quantities in nature. Nutrients are required as components of the microbial biomass. The need for these nutrients is very different from the need for oxygen and the carbon source. Nutrients are not consumed or converted and, unlike oxygen and carbon, no steady supply of nutrients is required. 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 the subsurface in anticipation of increased biodegradation rates, field data to date has not shown a clear relationship between increased rates and supplied nutrients.

Contaminant Concentration

The concentration of the contaminants may also affect biodegradation of the contaminant itself. Excessive quantities of a contaminant can possibly result in a reduction in biodegradation due to 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. In practice, fuel hydrocarbons in fuel-type mixtures do not generally appear to be toxic to the bioventing process. Other more soluble (i.e., phenolics) or less biodegradable compounds (i.e., TCE) do appear to present a toxicity problem and it has been reported that pure benzene solvent may be toxic (Leeson and Hinchee, 1995). Although a general relationship between bioventing rates and hydrocarbon concentration no doubt exists, the relationship is complex and is poorly understood.

Bioavailability

Another critical parameter affecting the extent of *in situ* bioremediation is bioavailability of the contaminant(s) of concern. Bioavailability is a general term to describe the accessibility of contaminants to the microorganisms. Compounds with greater aqueous solubilities and a lower affinity to partition into non-aqueous phase liquid (NAPL) or to sorb onto the soil generally are more bioavailable to soil microorganisms and are more readily degraded. For example, BTEX is preferentially degraded relative to alkanes (BTEX is more mobile and more soluble in pore water and therefore is more bioavailable). Bioavailability also depends on the suitability of the compound as a metabolic substrate or cosubstrate.

Relative Biodegradability

Any aerobically biodegradable contaminant such as fuel hydrocarbons can be degraded through bioventing. To be amenable to bioventing, a compound must generally:

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. In general, compounds with a low vapor pressure cannot be successfully removed by volatilization, but can be biodegraded in a bioventing operation. High vapor pressure compounds are gases at ambient temperatures, and these compounds may volatilize too rapidly to be easily biodegraded in a bioventing system. But, these compounds are typically only a small component of fuels and, due to their high volatility, will attenuate rapidly. Compounds with vapor pressures between 1 and 760 mm Hg may be amenable to either volatilization or biodegradation. Within this range lie many of the fuel hydrocarbon compounds of greatest regulatory interest such as BTEX compounds. Various petroleum fuels are more or less amenable to bioventing. Some components of gasoline are too volatile to easily biodegrade but are typically present at low overall concentrations and are attenuated rapidly. Most of diesel fuel constituents are sufficiently nonvolatile to preclude volatilization, whereas the constituents of JP-4 jet fuel are intermediate in volatility. Table 2-1 lists vapor pressures for selected fuel components.

Table 2-1. Vapor Pressures for Selected Fuel Components

Fuel Component	Vapor Pressure (mm Hg)
Isobutane	2,600
n-hexane	150
Benzene	95
Toluene	28
Ethylbenzene	9.5
p-xylene	8.7
m-xylene	8.3
o-xylene	6.6
Isopropylbenzene	3.2
1,3,5-trimethylbenzene	2.4
1,2,4-trimethylbenzene	2.0
Napthalene	0.2
Anthracene	0.00001
Pyrene	0.000007

Bioventing generally is not considered appropriate for treating compounds such as polychlorinated biphenyls (PCBs) and chlorinated hydrocarbons. However, through a cometabolic process, it may be possible to enhance the degradation of compounds such as TCE through bioventing. In laboratory studies, it has been shown that if toluene is present to provide the primary source of carbon, organisms that grow on toluene may be able to cometabolize TCE. More recently, it has been demonstrated that TCE can degrade *in situ* through the injection of oxygen and phenol into an aquifer (Hopkins et al., 1993). TCE removal of 88 percent was observed in the field, indicative of the potential for *in situ* cometabolic degradation of chlorinated compounds.

Estimation of Cleanup Times Using Oxygen Utilization and Biodegradation Rates

Oxygen Utilization Rates

A key indicator of *in situ* biologic activity is oxygen consumption. Because oxygen is the primary electron acceptor in aerobic microbial degradation pathways, uptake of oxygen by soil bacteria is a quantifiable indicator of hydrocarbon biodegradation. A decrease in the oxygen-utilization rate over time is an indicator of hydrocarbon biodegradation and contaminant removal and is expected as the contaminant concentrations are reduced. Long-term bioventing treatability studies have shown that oxygen-utilization rates decrease to rates that are approximately the same as in clean background soils (Stanin and Phelps, 1994). The *in situ* respiration test (ISR test) provides a simple field measurement tool to assess whether the microorganisms are metabolizing the fuel by observing oxygen utilization. Therefore, the ISR test is the most useful indicator of bioventing feasibility (see Sections 6, 7, and 9).

Cleanup-time estimations:

- *Oxygen utilization is a quantifiable indicator of fuel hydrocarbon biodegradation and indicates that all parameters affecting microbial processes are within an acceptable range.*
- *Oxygen utilization rates are used to estimate biodegradation rates.*

Biodegradation Rates

Oxygen-utilization rates are converted to hydrocarbon biodegradation rates using a conservative stoichiometric oxygen demand of 3.5 pounds of oxygen for every pound of hydrocarbon degraded (Hinchee et al., 1992). This relationship describes the oxidation of the hydrocarbon resulting in complete biological mineralization of the fuel (to carbon dioxide and water). Using measured or assumed physical parameters or laboratory measurements for values of air-filled porosity, soil bulk density, oxygen density, oxygen-utilization rate, and the mass ratio of hydrocarbon to oxygen required for mineralization, the rate of biodegradation can be expressed in terms of milligrams of fuel per kilogram of soil degraded each year (see Section 7 for details). Rates of carbon dioxide generation can also be used for estimating biodegradation rates, but this method is less reliable than using oxygen-utilization rates because little to no gaseous carbon dioxide production may be measurable due to the formation of carbonates in the soil carbonate cycle from the gaseous evolution of carbon dioxide produced during respiration (Hinchee et al., 1991a). Similar problems are encountered when using carbon dioxide evolution to quantify the biodegradation component of cleanup associated with soil vapor extraction systems (van Eyk and Vreeken, 1988).

Section 3
BIOVENTING AS A PRESUMPTIVE REMEDY

Based on a review of numerous sites at several Air Force installations across the United States (Section 4), the presumptive remedy for vadose zone soil contamination by fuel hydrocarbons has been determined to be bioventing. This technology will satisfy the removal objectives for the majority of Air Force sites with fuel-hydrocarbon contamination and will permit an early reduction of the mobility and quantity of fuel hydrocarbons in the soil. Bioventing can remove fuel hydrocarbons from vadose zone soils at most Air Force sites. Whether or not bioventing is an appropriate technology for specific Air Force sites will need to be decided based upon a demonstrated risk-based need to conduct source removal and confirmed through a site-specific evaluation of bioventing criteria (Section 6).

Selection of a Presumptive Remedy

The standard procedure for selecting a remedial action alternative for Corrective Action or non-time-critical removal actions is a three-step process that includes the following elements:

- *Identification of remedial alternatives, when a large set of alternatives is screened*
- *Detailed evaluation of the identified alternatives based upon effectiveness, implementability, and cost considerations*
- *Comparative analysis of the identified alternatives*

This extensive evaluation is designed to provide decision makers with sufficient information to justify the choice of a remedial alternative. However, EPA has recognized that at times site conditions are so well suited to a particular technology that the technology can be presumed to be appropriate without an exhaustive evaluation. This so-called presumptive remedy approach allows the selection of a remedial technology or process option which has been repeatedly shown to work within the range of conditions present at the site. In the specific instance where bioventing is to be employed for removing fuel hydrocarbons from soils, there is no need for a protracted evaluation procedure because decision makers are familiar with this technology.

This section justifies the selection of bioventing as a presumptive remedy for the remediation of fuel hydrocarbons in vadose zone soils by demonstrating that bioventing has advantages that strongly outweigh other considered remedial technologies. To support this contention, following sections (Sections 4 and 7) review engineering and economic data from treatability tests performed at 142 Air Force installation sites nationwide which have revealed that bioventing has almost universal application for remediating fuel-hydrocarbon-contaminated soils in a cost-effective manner.

Basis for Rejecting Non-Bioventing Alternatives

General Response Actions

Four general response actions --- apart from no-action alternatives --- that can be applied to fuel-hydrocarbon-contaminated soils:

- *Institutional controls*
- *Containment*
- *Removal*
- *Treatment (including bioventing)*

Each general response action can be achieved through one or more technologies, and each technology may have one or more process options. Not all options will be technically implementable at a given site. Only those options that pass an initial screening procedure are evaluated as remedial alternatives in a Corrective Action Plan (CAP) or a final Record of Decision (ROD) document. By focusing on alternatives usually considered for fuel-hydrocarbon-contaminated soils, the selection of technologies that would most likely be successful at Air Force and DOD sites for broader application can be facilitated. The general response actions noted above will therefore be considered in light of the remedial alternatives applicable at fuel-hydrocarbon-contaminated soils, as well as specific site conditions encountered at the 142 Air Force installation sites investigated during the Bioventing Initiative Project.

The technological processes generally considered for fuel-hydrocarbon-contaminated sites as potential action alternatives are: capping, deed restrictions, removal followed by treatment or disposal, soil vapor extraction (SVE), bioventing, soil flushing, and soil aeration. Except for SVE and bioventing, these processes are generally rejected as long-term, stand-alone remedies at numerous Air Force installation sites part of the Bioventing Initiative and Bioventing Follow-On Projects for the reasons indicated in Table 3-1, and discussed below.

Table 3-1. Rejected Long-Term, Stand Alone Remedial Alternatives

Alternative	Basis for Rejection
Capping	No reduction in soil contamination
Deed restrictions (Institutional controls)	Lack of permanence and long-term effectiveness
Excavation with disposal, thermal treatment, soil aeration, or landfarming	Short-term adverse health effects Difficult to implement (access; impact on other operations) Space and time requirements Residual contamination in unexcavated soils Air emissions High cost
Soil flushing	Limited effectiveness Incompatability with other remedies High cost
Soil vapor extraction	Not effective on low-volatile fuels Higher costs due to off-gas treatment, O&M, and air permitting

Capping (Containment)

Containment technologies are used to restrict the migration of fuel hydrocarbons to groundwater. Capping involves the placement of an impermeable layer (e.g., asphalt, concrete, synthetic membranes) over the site to prevent percolation through the contaminated zone and carrying fuel hydrocarbons to groundwater. Capping is rarely considered as a stand-alone remedy, although it can be selected to be used in conjunction with other selected remedies. As a supplemental remedy, capping of a site has the advantage of preventing or reducing the infiltration of water and subsequent leaching of contaminants from the vadose zone into groundwater. It also reduces fugitive dust emissions, as well as emissions of volatile contaminants from the soil to the air. However, capping is often one of the most expensive alternatives and does not reduce contaminant levels in soil.

Institutional Controls

This general response action limits access to contaminated areas, thereby eliminating exposure to hazardous substances. Limited access is commonly accomplished by one of two means: physical restrictions (e.g., security fences) or deed restrictions. Such actions do not reduce the mobility, toxicity, or volume of contamination in the soils, and do not constitute a permanent remedy. This alternative is usually not selected as a final remedy at a site, although it can be used as a temporary measure in conjunction with another remedy, such as bioventing and intrinsic remediation.

Excavation (Removal)

This general response action involves the excavation of contaminated material using ordinary construction equipment. The contaminated material can then be disposed of off-site or subjected to further treatment. Excavation is usually considered at many sites, and is often considered as part of a final remedy. Because excavation is expensive, it is generally considered only where relatively small volumes of contaminated soil are involved. Also, excavation is often impractical due to depth and physical constraints such as buildings, and on-site aboveground treatment options of excavated material generally have significant space and/or time requirements. Furthermore, increased restrictions on land disposal and the risk of becoming a potentially responsible party in future landfill remediation have made off-site disposal a less attractive option.

In Situ Treatment

In situ treatment technologies are those that involve treating the soil in place. Non-bioventing *in situ* alternatives normally considered for treatment of fuel-contaminated soils include SVE and soil flushing.

SVE is applicable for such soil contamination as long as the fuel is a highly volatile hydrocarbon product such as gasoline. As the volatility of fuels decreases from jet propulsion fuel to diesel to heating and waste oils, the potential application of SVE decreases, because this treatment technology requires a highly volatile contaminant to be effective. SVE does promote oxygenation and biodegradation similar to bioventing, but SVE does not have any advantages over bioventing for fuel-hydrocarbon soil contamination because the high flow rates, extraction, and off-gas treatment components of an SVE system are usually unnecessary to remediate a site and add significant costs to the remedial effort. The advantages of bioventing via air injection are discussed later in this section. SVE at fuel sites may however be a shorter-term first step at sites with high concentrations of volatiles that have a high potential for volatilization hazards due to underground utilities and other conduits, and the presence of on-site personnel.

Soil flushing is a technique where soil contaminants are transported to the groundwater and subsequently treated. Soil flushing is usually not selected as a final remedy because of its limited effectiveness, interference with other remedies such as venting, and its relatively high cost.

Ex Situ Treatment

Ex situ treatment requires removal before treatment, as discussed above. Thermal treatment, soil aeration and landfarming are *ex situ* processes that are normally considered for treatment of fuel-contaminated soils.

Low-temperature thermal treatment has been used to rapidly remove fuel hydrocarbons and to produce a soil which can be used for backfill, road base material, etc. Both mobile and fixed-base treatment plants are available. Thermal treatment provides a more rapid decontamination of soils but generally is more expensive and requires air permits and special soil handling procedures.

Soil aeration is an *ex situ* treatment process that involves excavation of the contaminated soil and spreading the soil on the ground to facilitate aeration. Aeration has distinct disadvantages due to the involvement of excavation (previously discussed), and emissions from soil aeration are difficult to capture and treat and often require permitting.

Landfarming is another *ex situ* treatment that initially involves excavation of the contaminated soil. The soil is then spread on the ground, and water and nutrients are mixed in periodically, and the soil is tilled to facilitate aeration. This treatment process can be advantageous since cleanup times can be relatively quick. However, landfarming comes with the problems of excavation as previously discussed, significant space is usually required for the treatment area, and leachate and volatile emissions must be controlled.

Basis for Selecting Bioventing - Advantages of Bioventing

Bioventing is a technology that is particularly advantageous for remediating vadose-zone soils contaminated with fuel hydrocarbons. Based on advantages discussed below, studies conducted by the Air Force (Section 4), and the previous discussions of other treatment alternatives, bioventing can be selected as a remedial action alternative for most sites at Air Force/DOD installations with fuel-hydrocarbon soil contamination.

Main advantages of bioventing:

- Bioventing by forced-air injection provides for superior oxygen transport compared with to flooding the contamination zone with water and dissolved oxygen (or alternative electron acceptor).
- Bioventing can remediate contamination in low-permeability soils due to diffusion of oxygen.
- Bioventing can be applied to sites contaminated with low-volatile hydrocarbons.
- Bioventing results in reduced air emissions compared with other venting techniques (SVE).
    - SVE = 5 to 100 pore volume exchanges per day
    - Bioventing = <1 pore volume exchange per day
    - Air injection vs. extraction
- Bioventing is one of the most cost-effective and efficient technologies for fuel hydrocarbon-contaminated sites.

Superior Oxygen Transport and Diffusion in Low-Permeability Soils

Previously, conventional enhanced bioreclamation processes used water to carry oxygen or an alternative electron acceptor to the contaminated zone. This was common whether the contamination was present in the groundwater or in the unsaturated zone (Raymond, et al., 1976). In most cases where water is used as the oxygen carrier, the solubility of oxygen is the limiting factor for biodegradation. If pure oxygen is used and 40 mg/L of dissolved oxygen is achieved, approximately 88,000 lb of water must be delivered to the contaminated zone to degrade 1 lb of hydrocarbon. If 500 mg/L of hydrogen peroxide is successfully delivered, then approximately 13,000 lb of water must be used to degrade the same amount of hydrocarbon. However, with bioventing, air is the carrier mechanism for delivering oxygen to the contaminated zone. When air is used, only 13 lb of air must be delivered to provide the minimum oxygen required to degrade 1 lb of hydrocarbon. Since costs associated with pure oxygen and hydrogen peroxide in water can be relatively high, the use of gas-phase (air) delivery results in significant reduction in the cost associated with supplying the oxygen.

Air has a greater diffusivity than water. Water pumped to the subsurface will flow through the more permeable pathways, but oxygen can not be delivered to the less-permeable zones. In a gaseous system, diffusion can be expected to take place at rates several orders of magnitude greater than rates in a liquid system. Although it is not realistic to expect diffusion to aid significantly in water-based remediation, diffusion of oxygen in a gas-phase system may be a significant mechanism for oxygen delivery to less-permeable zones.

Applications for Low-Volatile Fuel Hydrocarbons

Aerobically biodegradable compounds, such as fuel hydrocarbons, potentially can be degraded through bioventing. To date, bioventing has been applied primarily to fuel (petroleum) hydrocarbons (Downey et al., 1993; Leeson et al., 1993); however, bioventing of polycyclic aromatic hydrocarbons (PAHs) (Lund et al., 1991; Hinchee and Ong, 1992) and bioventing applied to an acetone, toluene, and naphthalene mixture (Hinchee and Ong, 1992) have been implemented successfully. Therefore, bioventing can be applied to aerobically biodegradable compounds that cover a wide range of volatility. For example, compounds (e.g. diesel fuel and PAHs) with a low vapor pressure (< 1 mm Hg) cannot be successfully removed by volatilization (SVE), but can be biodegraded in a bioventing application.

Air Injection vs. Extraction

Aeration of the vadose-zone soil contamination zone may be accomplished in a bioventing system with either air injection or extraction (or a combination of the two). Bioventing can implement air injection because bioventing is designed to minimize volatilization and optimize biodegradation, since bioremediation is the major cleanup mechanism. Air injection is the preferred configuration since it will result in a minimal discharge of VOCs to the atmosphere (with a flow rate of < 1 pore volume exchange per day) and is less expensive to operate and maintain than air extraction systems. In general, air can be injected at flow rates low enough to avoid surface emissions altogether. This is generally possible at sites contaminated with JP-4 or JP-5 jet fuel, diesel, and other contaminants of similar or lesser volatility. It is more difficult with gasoline, although successful systems using only air injection have been reported at gasoline-contaminated sites (Kampbell, 1993).

If air injection is implemented, and the contaminants are volatile, some will migrate in the gas phase into surrounding soil where they can biodegrade. This has the advantage of creating an expanded *in situ* bioreactor (Leeson and Hinchee, 1995). Given adequate oxygen, the volatilized hydrocarbons will biodegrade in these surrounding uncontaminated soils, and the total mass of contaminants biodegraded may be substantially greater than with systems such as air extraction where an expanded bioreactor is not created. Also, as air is injected into the vadose zone, the positive pressure created results in a depression of the water table. If the capillary fringe zone is highly contaminated (common at fuel contamination sites), the capillary fringe will more effectively be treated since the air-filled porosity is increased in this zone. With air extraction, a partial vacuum produced in the soil results in the water table rising. This upconing can saturate much of the contaminated soil and reduce treatment efficiency due to a reduction in air-filled porosity.

Air extraction systems, in contrast to injection systems, usually require an explosion-proof blower with explosion-proof wiring. Extraction systems usually require permitting because they result in point-source emissions, and the extracted soil gas may also require treatment in some instances. This impacts remediation costs significantly. Also, condensed liquids must be collected and disposed. Under some circumstances, extraction may need to be incorporated into an air injection system design due to nearby basements, utility corridors, or occupied surface structures (to prevent the accumulation of explosive or toxic vapors into these structures). However, numerous options are available that may allow air injection at sites with structures at risk or with property boundaries nearby. These options include monitoring the atmosphere in the structure to verify that no contaminant has entered; use of air extraction coupled with reinjection to protect the building; or use subslab depressurization.

Efficiency and Cost-Effectiveness

Compared with other remedial technologies applicable to soils contaminated with fuel-hydrocarbons, bioventing is a cost-effective alternative in an era of funding shortfalls and reduced manpower. This is primarily due to the fact that *in situ* bioventing eliminates expensive off-gas treatment often required with conventional soil vapor extraction systems and thereby can reduce remediation costs by as much as 50 percent on sites where vapor emissions must be treated. Moreover, bioventing systems are mechanically simple with minimal mechanical and electrical parts. If the system is operated in injection mode, a simple visual system check to ensure that the blower is operating within its intended flow rate, pressure, and temperature range would be required. These system checks can be done by someone onsite because little technical knowledge is required. The blowers used for air injection are usually small and do not require periodic oil changes. Only minor maintenance such as replacing filters, flow meters, or gauges may be necessary. The typical blowers used last for several years and should not need replacement.

Section 4
STUDIES SUPPORTING THE USE OF BIOVENTING AT AIR FORCE SITES

Although bioventing was first applied by the Dutch engineer J. Van Eyk (van Eyk and Vreeken, 1988), researchers from the US Air Force have made significant advances in the understanding of soil microorganism processes and *in situ* monitoring techniques. During the early 1990's, numerous publications on this subject have been authored by Air Force sponsored researchers, including a *Test Plan and Technical Protocol for Bioventing* (Hinchee et al., 1992), which has been distributed to over 1,500 Department of Defense (DOD) environmental managers and their consultants to standardize bioventing procedures. This document was reviewed and endorsed by USEPA's Risk Reduction Engineering Laboratory, and in a letter to EPA Regional Administrators, the Deputy Assistant Administrator of EPA's Office of Solid Waste and Emergency Response supported the protocol and requested cooperation from the EPA regions. The technical protocol was necessary for the Bioventing Initiative Project (discussed below) to ensure the consistent collection of a large data set used to statistically examine site-specific factors which positively and negatively impact bioventing success. As more sites have been tested, the protocol has evolved to include improved field techniques and data requirements (Downey and Hall, 1994). In addition, the Air Force has sponsored technology transfer conferences attended by Air Force and DOD personnel and has encouraged bioventing development in the private section through presentations at several national conferences.

Bioventing Initiative Project - General Overview

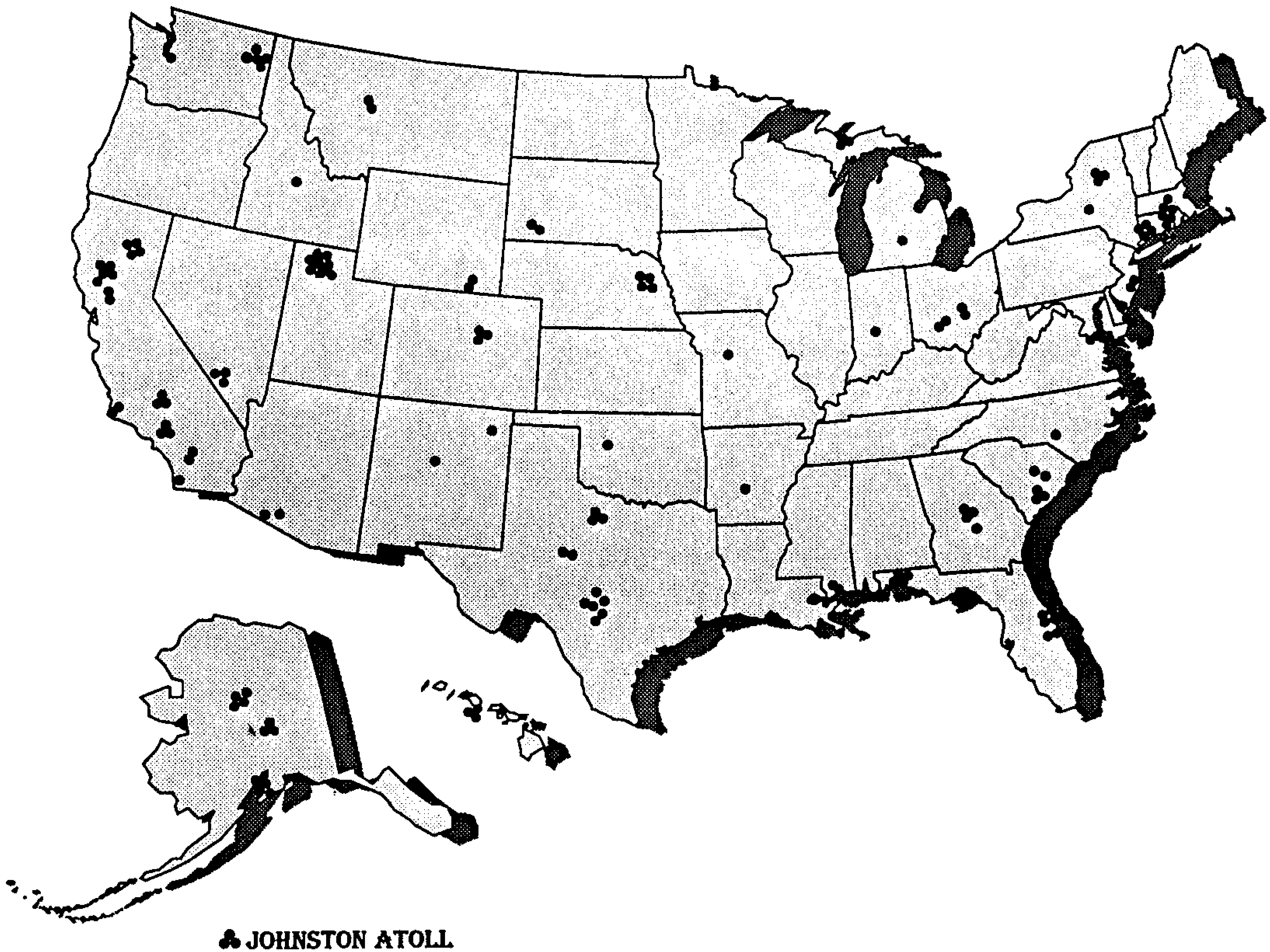
Air Force investment in this technology has been driven by the need to remediate an estimated 2,000 petroleum-contaminated sites located throughout the United States. Between April 1992 and July 1995, initial bioventing tests were completed at 142 Air Force sites as part of the Bioventing Initiative Project sponsored and directed by the Air Force Center for Environmental Excellence (AFCEE) Technology Transfer Division. Figure 4-1 illustrates the geographic and climatic diversity of test locations. With the endorsement of the EPA, the bioventing technology has now been approved for application in 31 states and in all 10 EPA regions. These sites are under CERCLA and RCRA jurisdiction as well as regulated under special state programs. On smaller sites, many of these treatability (pilot scale) systems are providing full-scale remediation. This major field initiative is producing valuable data which are being used by the Air Force and the EPA to develop both feasibility screening tools and a comprehensive procedures and practices manual for bioventing applications (Leeson and Hinchee, 1995).

To date, this Bioventing Initiative is demonstrating that the technology is effective at numerous sites under widely varying conditions (Miller et al., 1993; Battelle, 1995 in progress). Beginning in 1995 as part of the Bioventing Follow-On Project, many of these bioventing initiative sites began undergoing additional monitoring for longer-term performance, some of these bioventing systems are being expanded to full-scale operations, and some sites are being sampled to provide data for a "No Further Action" document. These bioventing projects follow extensive research at Hill AFB, Utah (Hinchee et al., 1993; Dupont et al., 1991; Hinchee et al., 1991b and 1991c) and Tyndall AFB, Florida (Miller and Hinchee, 1990a and 1990b; Miller, 1990; Miller et al., 1991; Sorenson et al., 1991). Specialized research is continuing at Hill AFB, Utah (Sayles et al., 1992a) and Eielson AFB, Alaska (Sayles et al., 1992b).

FIGURE 4-1

AIR FORCE BIOVENTING INITIATIVE LOCATIONS

AS OF 1 JULY 1994



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As of July 1995, extended bioventing systems were operating at 119 sites on 54 Air Force installations. Table 4-1 summarizes the overall progress of the Bioventing Initiative project. Table 4-2 includes several details, including costs, on many of these sites.

Table 4-1. Bioventing Initiative Status

Tasks	Number of Bases	Number of Sites
Initial Site Visits	59	158
Completed Work Plans	57	148
Initial Testing Complete	54	142
1-Year Tests Underway	54	119
Construction in Progress	1	1
6-Month Testing Complete	51	112
Confirmatory Soil Sampling Complete	46	95
Natural Attenuation Sites	7	18

Bioventing Initiative Project - Results

Using the technology protocol documents (Hinchee et al., 1992; Downey and Hall, 1994), initial testing was conducted at each site to determine whether bioventing was feasible. Based on the initial testing, a decision was made whether to install a bioventing system for one year of operation. At the majority of sites, a bioventing system was installed for the one-year operational period. On nearly 20 sites, natural attenuation was sufficient to sustain biodegradation without mechanical air injection. At the end of this time 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 remediated sufficiently.

At each site in which a bioventing system was installed, a series of data was selected:

- *Initial data consisting of soil and soil-gas sampling, in situ respiration testing results, and soil-gas permeability testing results.*
- *One-year soil and soil-gas sampling and in situ respiration testing results.*

Initial test data from 142 sites has revealed that bioventing has almost universal application for remediating fuel hydrocarbon-contaminated soils. A detailed statistical analysis is underway to determine what factors produce the highest rates of *in situ* biodegradation. While warm, moist sandy soils are optimum for oxygen distribution and microbial growth, and have produced higher than average biodegradation rates, the most encouraging results have been obtained at sites with less than optimum conditions. A summary of initial site conditions and their apparent impact on the bioventing process is provided in the following discussions.

TABLE 4.2
SUMMARY OF AFCEE BIOVENTING INITIATIVE PILOT TEST SYSTEMS

Base	Site	Number of VMPs [a]	Number of VWs	Vent Well (VW) Identifier	VW Screened Interval[b] (feet)	HVW[c] Depth (feet)	Blower Size and Type	Cost[d]
FE Warren AFB, WY	FTA-1	3	1	VW	3-8	NA[e]	3 HP Positive Disp.	
	Site 1 (Spill Site)	3	1	VW	8-13	NA	3 HP Positive Disp.	$53,545.30
Hill AFB, UT	Bldg 924	6	1	HVW [f]	Horiz: 100 feet long	12	2 HP Regenerative	
	Bldg 204.1	3	1	VW [f]	10-50	NA	1 HP Regenerative	
	Bldg 228	1	1	VW [f]	10-40	NA	1 HP Regenerative	
	Bldg 214	2	1	VW [f]	5-60	NA	1 HP Regenerative	
	Site 40002	2	1	VW [f]	5-45	NA	1 HP Regenerative	
	Site 1705	2	1	VW [f]	10-20	NA	1 HP Regenerative	
	Site 510.8	3	1	VW	34-64	NA	1 HP Regenerative	
	Site 388	5	2	VW1 [f]	25-75	NA	2 HP Regenerative	
				VW2	55-120	NA		$207,171.10
Offutt AFB, NE	LPD (Bldg 528)	3	1	VW	3.5-8.5	NA	1 HP Regenerative	
	Bldg 30 Site	3	1	VW	3.5-8.5	NA	1 HP Regenerative	
	Bldg 406 (2 yr)	3	4	VW1	6-16	NA	2 HP Regenerative	
				VW2	6-16	NA		
				VW3	5-15	NA		
				VW4	5-15	NA		
	POL Area	3	1	VW	7.5-12.5	NA	1 HP Regenerative	$233,304.55
Plattsburgh AFB, NY	FTP-3	3	1	VW	6-36	NA	2 HP Regenerative	
	FTP-2	3	1	VW	10-35	NA	Manifolded to FTP-3	
	FTP-1	3	1	VW	10-45	NA	2 HP Regenerative	
	FTP-4	3	1	VW	6-36	NA	2 HP Regenerative	$207,372.00
K.I. Sawyer AFB, MI	POL Area (ST-04)	3	1	VW	14-69	NA	2 HP Regenerative	
	FT Area(06)	3	1	VW	10-65	NA	2 HP Regenerative	
	FT Area(07)	3	1	VW	10-60	NA	2 HP Regenerative	$153,057.05
Battle Creek ANGB, MI	IRP Site 3 FTA	3	1	VW	10-30	NA	1 HP Regenerative	$44,952.95
McGuire AFB, NJ	JP-4 Pipeline SS	3	1	VW	5-15	NA	1 HP Regenerative	$69,863.05
Tinker AFB, OK	POL Strg Area C	3	1	VW	7-17	NA	1 HP Regenerative	$47,707.10
AFP4, TX	FSA-1	3	1	VW	8-23	NA	1 HP Regenerative	
	FSA-3	3	1	VW	5-15	NA	1 HP Rotary Vane	$72,882.90
Dyess AFB, TX	FT40	4	1	VW	6.9-16.5	NA	1 HP Regenerative	
	FT41	3	1	VW	6.4-16	NA	1 HP Regenerative	$59,809.45

TABLE 4.2 (Continued)
SUMMARY OF AFCEE BIOVENTING INITIATIVE PILOT TEST SYSTEMS

Base	Site	Number of VMPs [a/]	Number of VWs	Vent Well (VW) Identifier	VW Screened Interval[b/] (feet)	HVW[c/] Depth (feet)	Blower Size and Type	Cost[d/]
Kelly AFB, TX	FC-2 (FTA)	3	1	VW	7-19	NA	2 HP Regenerative	
	S-4 (JP-4 Spill)	3	1	VW	7-17	NA	1 HP Regenerative	
	Bldg 2093[g/]	3	1	VW	7-17	NA	1.5 HP Rotary Vane	
	D-10	3	1	VW	6-16	NA	1 HP Regenerative	$158,758.00
Beale AFB, CA	IRP Site 3	4	1	VW	9.6-23.9	NA	2 HP Regenerative	
	IRP Site 18	3	1	VW	10-60	NA	2 HP Regenerative	
	IRP Site 11	3	1	VW	10-50	NA	1 HP Regenerative	$201,535.65
Travis AFB, CA	IRP Site 1	4	1	VW	5-12	NA	1 HP Regenerative	$97,565.45[h/]
Vandenberg AFB, CA	Base Serv Stat.	4	1	VW	4.7-22.7	NA	2 HP Regenerative	
	Site 6454	3	1	VW	5-70	NA	1 HP Regenerative	330,295.90[i/]
Edwards AFB, CA	IRP Site 16 (JP-4)	3	1	VW	8-13	NA	1 HP Regenerative	
	IRP Site 21 (Jet)	3	1	VW	7-14.5	NA	1 HP Regenerative	
	Site 43(D.T.)	1	1	VW	4.5-15	NA	1 HP Regenerative	$145,839.25
March AFB, CA	IRP Site 35C	3	1	VW	4-11	NA	1 HP Rotary Vane	$98,047.10[h/]
LA AFB, CA	Bldg 125	1	1	VW	7-37.5	NA	1/10 HP Rotary Vane	
	Bldg 241	3	1	VW	10-40.5	NA	1 HP Regenerative	
	Gate 3	3	1	VW	14.5-55	NA	1 HP Regenerative	$152,790.05[h/]
Cape Canaveral, FL	FTA-2	4	3	VW	3-8	NA	1 HP Regenerative	
	FAC 44625 D UST	3	1	VW	3-8	NA	1 HP Regenerative	
	FAC 44625 E UST	3	1	VW	3-8	NA	1 HP Regenerative	
	FAC 1748 UST	4	1	VW	3-8	NA	1 HP Regenerative	$150.712.95
Patrick AFB, FL	FTA-2	5	1	HVW	Horiz: 20 feet long	3.5	1 HP Regenerative	
	Bx Serv. Stat.	5	1	HVW	Horiz: 30 feet long	3.5	1 HP Regenerative	$167,998.50[i/]
Charleston AFB, SC	FTA-03	4	1	HVW	Horiz: 20 feet long	3.5	1 HP Regenerative	
	JP-4 (Bldg 93)	4	2	VW1&VW2	5.3-11.6	NA	1 HP Regenerative	$138,320.00[h/]
Hickam AFB, HI	Area H	3	1	VW	9.5-19.5	NA	1.5 HP Rotary Vane	
	Area K	3	1	VW	4.3-9.3	NA	1.5 HP Rotary Vane	
	Site 2 FSA	4	1	VW	15.75-45.75 and 65.75-100.75[k/]	NA	2 HP Regenerative	$182,137.15
AFP PJKS, CO	UST OTL	4	1	VW	5-20	NA	1.5 HP Rotary Vane	$46,207.40

TABLE 4.2 (Continued)
SUMMARY OF AFCEE BIOVENTING INITIATIVE PILOT TEST SYSTEMS

Base	Site	Number of VMPs [a]	Number of VWs	Vent Well (VW) Identifier	VW Screened Interval[b] (feet)	HVW[c] Depth (feet)	Blower Size and Type	Cost[d]
Grissom AFB, IN	JP-4 Trans Stat.	5	8	VW1	3.7-8.7	NA	5.5 HP Regenerative	
				VW2	4-12	NA		
				VW3	4-11.5	NA		
				VW4	4-11.5	NA		
				VW5	4.5-11.5	NA		
				VW6	4-11.5	NA		
				VW7	4.5-11.5	NA		
				VW8	4.5-11.5	NA		$88,303.90
Randolph AFB, TX	Tank 20	3	3	VW1 TO VW3	5-15	NA	1.5 HP Rotary Vane	$45,743.00
Kirtland AFB, NM	FT-13	3	1	VW	5-30	NA	1 HP Regenerative	$76,732,10[h]
Bolling AFB, D.C.	Bldg 18	2	1	VW	6-21	NA	1 HP Regenerative	
	Former Tnk Fm	6	4	VW1 TO VW4	5-15	NA	1&5 HP Rotary Vanes	$104,197.60
McClellan AFB, CA	Tank Farm 2	3	1	VW	10-35	NA	1 HP Regenerative	
	Tank Farm 4	3	1	VW	10-25	NA	1 HP Regenerative	
	SA-6	2(3)[l]	(2)[l]	VW1	25-100	NA	2 HP Regenerative	
				VW2	15-100	NA		
	PRL T-46	1	3	VW	8-45	NA	1 HP Regenerative	
	Davis GCS	4	1	VW	10-55	NA	1 HP Regenerative	
	Capehart GS	1(8)[l]	1	VW	10-105	NA	1 HP Regenerative	$540,819.55[h]
Westover AFB, MA	Bldg 7701[m]	3	1	VW	Info. not available	NA	Info. not available	
	FA7705	3	1	VW	6-21	NA	1 HP Regenerative	$61,770.75
Malmstrom AFB, MT	PH2	3	1	VW	5-10	NA	1.5 HP Rotary Vane	
	BFS	3	1	VW	5-10	NA	1 HP Regenerative	$63,086.35
Hanscom AFB, MA	BSS Bldg 1639[m]	3	1	VW	4-7	NA	Info. not available	
	Bldg 1812[m]	3	1	VW	3.4-7	NA	Info. not available	$43,281.55
Fairchild AFB, WA	PS-1A	3	1	VW	4-8	NA	1 HP Regenerative	
	PS-2	3	1	VW	5-10	NA	1 HP Regenerative	
	PS-1B	3	1	VW	4.5-8.8	NA	1 HP Regenerative	
	Bldg 2034	3	1	VW	5-10	NA	1 HP Regenerative	
	Bldg 2035	3	1	VW	5-10	NA	1 HP Regenerative	$290,124.55

TABLE 4.2 (Continued)
SUMMARY OF AFCEE BIOVENTING INITIATIVE PILOT TEST SYSTEMS

Base	Site	Number of VMPs [a/]	Number of VWs	Vent Well (VW) Identifier	VW Screened Interval[b/] (feet)	HVW[c/] Depth (feet)	Blower Size and Type	Cost[d/]
Elmendorf AFB, AK	ST 61	2	1	VW	5-20	NA	1 HP Regenerative	
	Valve Pit 3-4	2	1	VW	15-22	NA	1 HP Regenerative	
	ST 71	2	1	VW	5-15	NA	1 HP Regenerative	
	PH 3	2	1	VW	15-23	NA	1 HP Regenerative	$147,879.40
Ellsworth AFB, SD	Area D	3	2	VW1	10-17	NA	1 HP Regenerative	
				VW2	5-10	NA		
	Bldg 102	3	1	VW	8-18	NA	1 HP Regenerative	$71,532.90
Eglin AFB, FL	FTA Hurlburt	3	1	VW	2-7	NA	1 HP Regenerative	
	Eglin FTA	3	1	VW	5-40	NA	2 HP Regenerative	$120,977.40
Little Rock AFB, AR	SS18	4	1	VW	3-10	NA	1 HP Regenerative	$63,794.60
Pease AFB, NH	Area A	6	1	HVW	Horiz: 40 feet long	7	5 HP Rotary Vane	
	Area B	4	9	VW1 TO VW9	5-15	NA	5 HP Rotary Vane	$279,317.15
Nellis AFB, NV	Site 27	3	1	VW	55-80	NA	1 HP Regenerative	
	Site 28	3	1	VW	30-65	NA	1 HP Regenerative	
	Site 44	3	1	VW	18-43	NA	1 HP Regenerative	$158,806.15
Davis-Monthan, AZ	Site 35	8	4	VW1	223-233	NA	2 HP Regenerative	
				VW2	163-183	NA		
				VW3	105-120	NA		
				VW4	60-80	NA		
	Site 36	3	1	VW	16.5-96.5	NA	1 HP Regenerative	$432,007.80[n/]
Cannon AFB, NM	SWMU 70	3	1	VW	10-110	NA	1 HP Regenerative	$126,286.40
Shaw AFB, SC	FTA-01	4	2	VW1&VW2	5.5-9.5	NA	2 HP Rotary Vane	
	Site SS-15	3	1	VW	12-41	NA	1 HP Regenerative	$120,025.60
Ft. Drum, NY	Area 1595 FSA	3	1	VW	5-10	NA	1 HP Regenerative	$55,914.75
Mt. Home AFB, ID	POL Area	3	1	VW	4.2-18.2	NA	1 HP Regenerative	$55,418.85
Camp Pendleton, CA	Bldg 13115	4	2	VW1	5.75-39.25	NA	1 HP Regenerative	
				VW2	3.75-14	NA		$85,151.50

TABLE 4.2 (Continued)
SUMMARY OF AFCEE BIOVENTING INITIATIVE PILOT TEST SYSTEMS

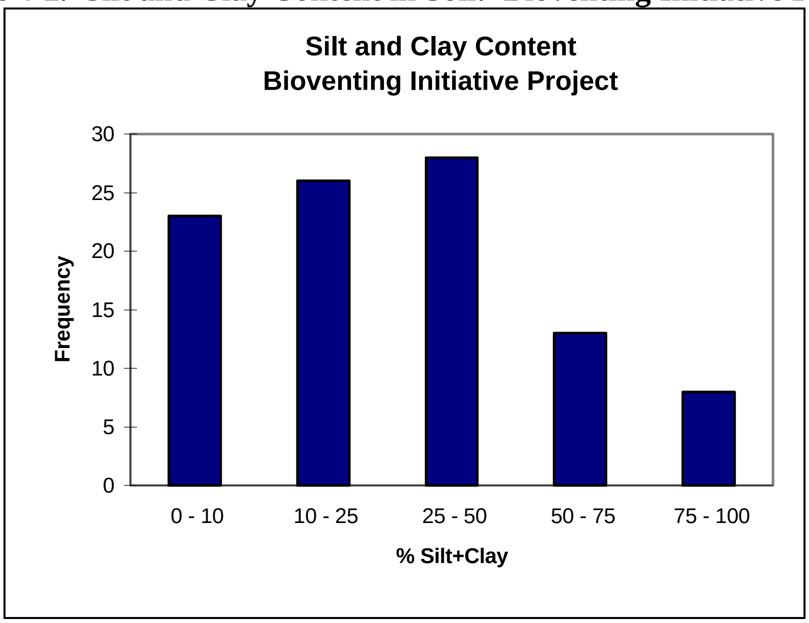
Base	Site	Number of VMPs [a/]	Number of VWs	Vent Well (VW) Identifier	VW Screened Interval[b/] (feet)	HVW [c/] Depth (feet)	Blower Size and Type	Cost[d/]
USCG Supp. Cen, Kodiak, AK	Site 6B T191	2	1	VW	4.2-19.2	NA	2 HP Regenerative	$68,996.65
Pope AFB, NC	ST-08	4	2	VW1 VW2	5.3-12.2 5.1-12	NA NA	5 HP Rotary Vane	$81,916.55[o/]

a/ VMP = Vapor monitoring point.
b/ Unless otherwise noted, screened interval provided is for vertical vent wells.
c/ HVW = Horizontal vent well.
d/ Value shown reflects total cost as of April 19, 1996 for work performed at each base as part of the Bioventing Initiative Project.
e/ NA = Not applicable.
f/ Initial drilling, soil sampling, and installation costs for this well not included as it was installed by another contractor.
g/ System was abandoned after Kelly AFB decided to excavate soils to make site available for reuse.
h/ Value includes costs for sites which are not shown, but for which initial planning and initial testing was performed. Bioventing systems were not installed at all sites.
i/ Cost includes over $120,000 for testing of Purus PADRE™ vapor treatment system at base service station site.
j/ Cost includes over $70,000 for testing of VR system internal combustion engine and Biocube™ system at BX service station site.
k/ This vent well has two screened intervals; the interval from 45.75 to 65.75 feet was cased off to prevent perched water intrusion (perched water was encountered 52 to 57 feet below ground surface.
l/ VMPs and/or VWs were installed at the site by other contractors. Number shown without parentheses represents number installed under bioventing initiative contract. Number in parentheses ( ) represents total number.
m/ Initial testing at this site performed by another contractor.
n/ Costs significantly higher for this Base due to the installation and 1-year operation of a soil vapor extraction system internal combustion engine and an autovalving system at Site 35.
o/ Value includes costs for work initially performed at a Langley AFB, VA site, where pilot testing was not completed.

Soil Gas Permeability Results

A grain-size analysis was completed on several samples from each site. Figure 4-2 illustrates the relative distribution of fine-grained soils (% silt plus clay) which have been encountered at test sites. Sufficient soil-gas permeability has been demonstrated at numerous sites with silt and clay contents exceeding 80 percent by weight (Downey et al., 1992; Phelps et al., 1995). Approximately 20 percent of the sites tested contain greater than 50 percent silt and clay fractions. Oxygen distribution has generally been uniform in soils where darcy values exceed 0.1; limited data are available for soils where darcy values of less than 0.1. In general, the calculated darcy values have exceeded literature values (Johnson et al., 1990) given for silt and clay soils. This is likely due to the heterogeneous nature of most soils, which contain thin layers of coarser sands that aid in air distribution. At approximately half of the sites tested, the radius of oxygen influence from a single vent well is equal to or larger than the contaminated area. Continued bioventing at these sites should result in full-scale remediation. Perhaps the greatest limitation to air permeability is excessive soil moisture. A combination of high moisture content and fine-grained soils has made bioventing infeasible at only two of the 142 test locations.

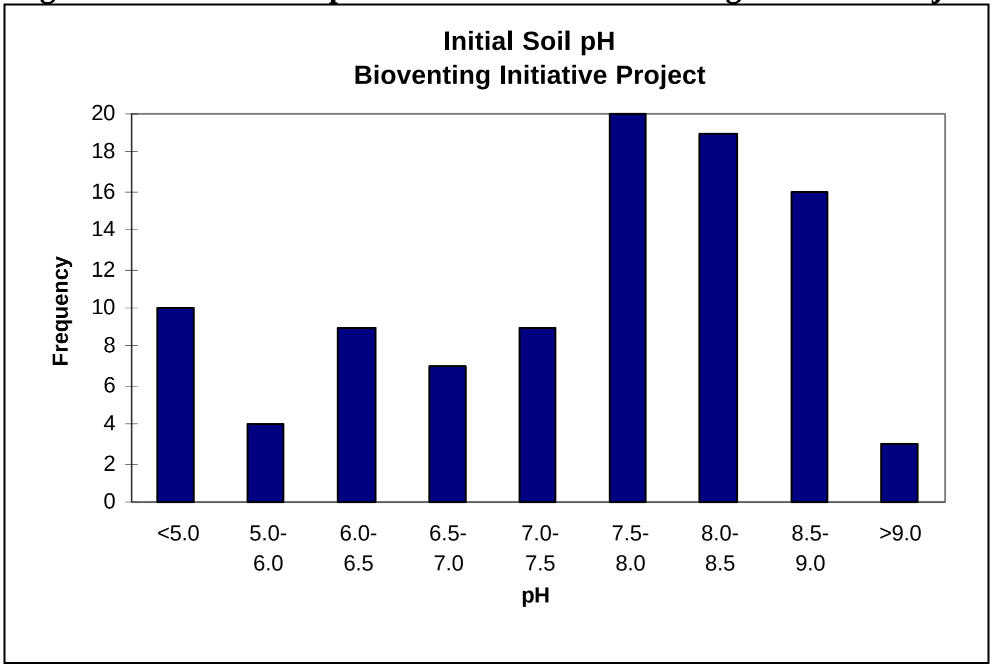
Figure 4-2. Silt and Clay Content in Soil: Bioventing Initiative Project



Biodegradation Factor - Soil pH

Figure 4-3 illustrates the range of soil pH found at the Bioventing Initiative sites to date. In general, the majority of sites are slightly alkaline and fall within the optimal pH range of 5 to 9 for microbial activity. However, microbial respiration has been observed at all sites, even in soils with pHs that fall outside this optimal range. A study of the relationship between pH and oxygen utilization rates shows that soil pH is of minor significance when bioventing at most sites (Leeson and Hinchee, 1995).

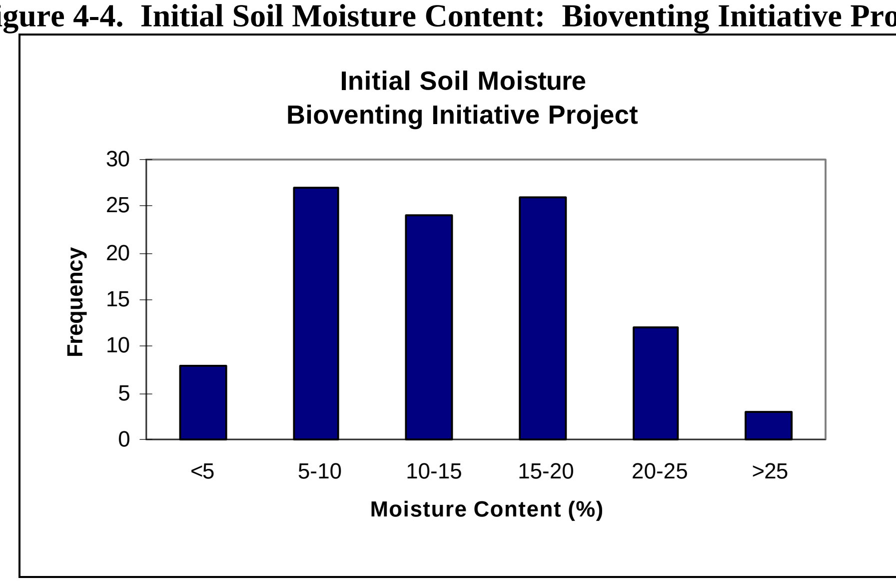
Figure 4-3. Initial Soil pH Values in Soil: Bioventing Initiative Project



Biodegradation Factor - Soil Moisture

The range of initial soil moisture content measured at the Bioventing Initiative sites is shown in Figure 4-4. The lowest soil moisture content measured was 2 percent, and microbial activity was still observed in these soils. Several test sites in semi-arid locations have sustained biodegradation rates with moisture levels al low as 3 to 5 percent by weight.

Figure 4-4. Initial Soil Moisture Content: Bioventing Initiative Project



To date, a strong correlation has not been recorded between moisture content and oxygen utilization rate, although a slight positive relationship has been observed. It is often assumed that air injection would dry out the soil to a point which would be detrimental to microbial growth, necessitating humidification of the injected air. Simple calculations illustrate that over a 3-year period, moisture loss is minimal; water is a byproduct of mineralization (biodegradation) and is generated at a rate of 1.5 lb water for every 1 lb of hydrocarbon degraded (Battelle, 1995, in progress). Excessive soil moisture, in excess of 85 percent field capacity, can reduce soil gas permeability and oxygen influence.

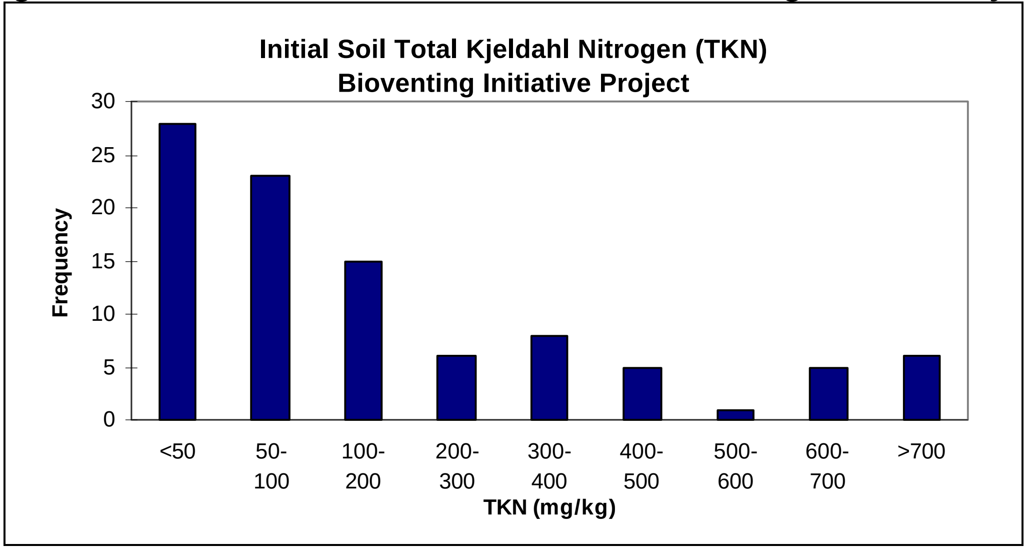
Biodegradation Factor - Temperature

Thermocouples have been installed at several depths at all Bioventing Initiative sites to monitor seasonal temperature changes and their impact on respiration rates. Biological activity has been measured at Eielson AFB, Alaska in soil temperatures as low as 0 °C (Sayles, 1992b). Previous research has shown that the vanHoff-Arrhenius equation provides a good estimate of temperature effects on soil microbial activity (Miller, 1990). This relationship predicts a doubling of microbial activity for every 10°C increase in temperature. Bioventing will more rapidly degrade fuel residuals during summer months, but some remediation occurs in soil temperatures down to 0 °C.

Biodegradation Factor - Nutrient Supply

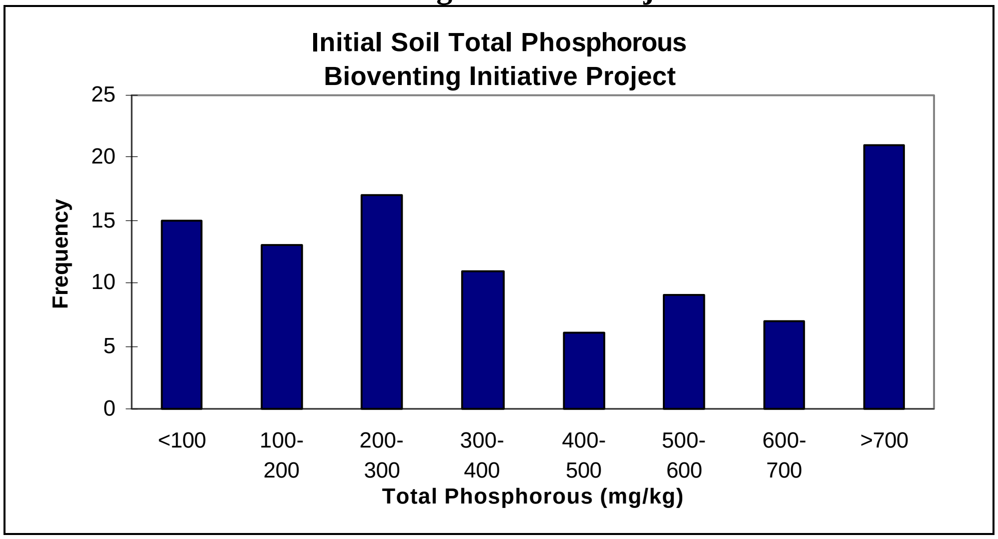
Nitrogen and phosphorous are among several nutrients known to be required to support microbial growth, and they are required in the greatest concentrations. Therefore, nitrogen and phosphorous are often the nutrients that are most likely to be limiting. Concentrations of total Kjeldahl nitrogen (TKN) and total phosphorous at the Bioventing Initiative sites are shown in Figures 4-5 and 4-6, respectively.

Figure 4-5. Initial TKN Concentrations in Soil: Bioventing Initiative Project



Natural nutrient levels as low as 20 mg/kg TKN and 3 mg/kg total phosphorous have been sufficient to sustain biological respiration at sites when the most limiting element, oxygen, is provided. Although optimal ratios of carbon, nitrogen, and phosphorous (250:10:1 ratio of C:N:P) are not available at all sites, the natural nutrient levels have been sufficient to sustain some level of biological respiration at all of the Bioventing Initiative sites. The statistical relationship between oxygen utilization rates and TKN and total phosphorous show no correlation for total phosphorous and only a slight correlation for TKN. This emphasizes that the natural nutrient level is sufficient for microbial activity (Leeson and Hinchee, 1995). A major question still being studied by the Bioventing Initiative Project is whether or not sites with high natural nutrient levels exhibit higher long-term respiration rates than low-nutrient sites.

Figure 4-6. Initial Total Phosphorous Concentrations in Soil: Bioventing Initiative Project



Rates of Oxygen Utilization and Biodegradation

Results shown in Figure 4-7 indicate a wide variation in oxygen utilization rates with a large number of sites in the 3 to 12 percent per day range. Using a conservative stoichiometric oxygen demand of 3.5 pounds of oxygen for every pound of hydrocarbon degraded, oxygen utilization rates were converted into milligrams of fuel biodegraded per kilogram of soil each year. Figure 4-8 illustrates the wide variation in estimated fuel biodegradation rates occurring at Bioventing Initiative sites. Using a range of 500 to 2,500 milligrams of fuel biodegraded per kilogram of soil per year, an average air-filled soil porosity of 0.15, and average initial TRPH levels of 2,000 to 3,000 mg/kg, typical remediation times to achieve a 100 mg/kg TRPH clean-up level are approximately 1 to 5 years.

Figure 4-7. Initial Oxygen Utilization Rates: Bioventing Initiative Project

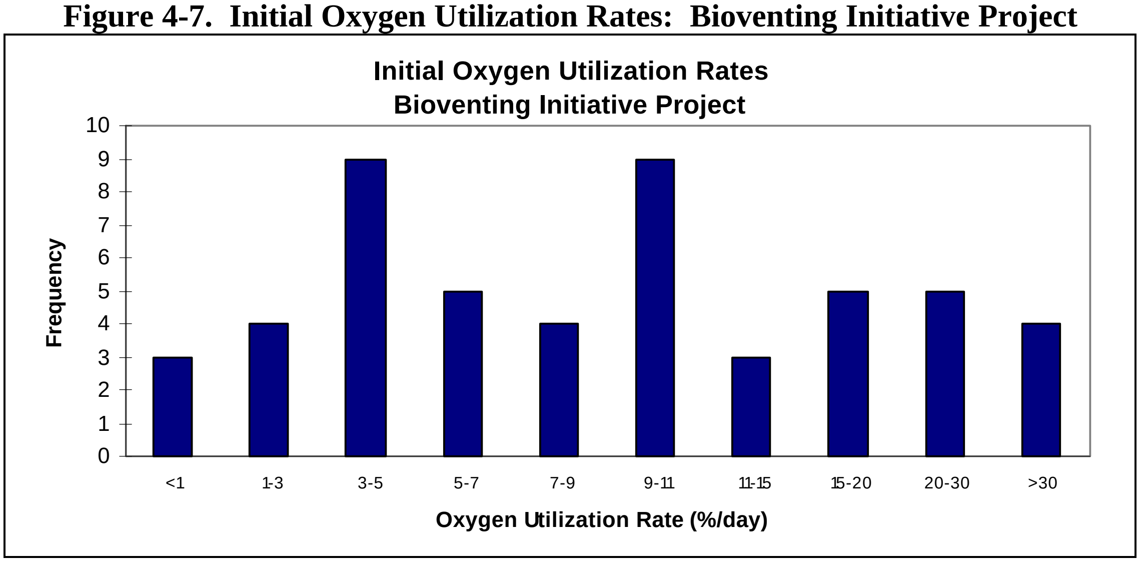
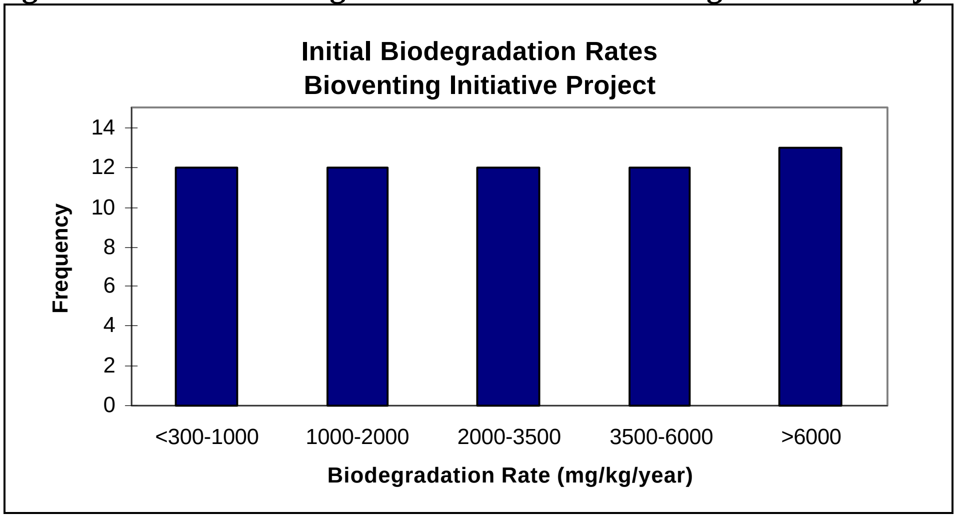


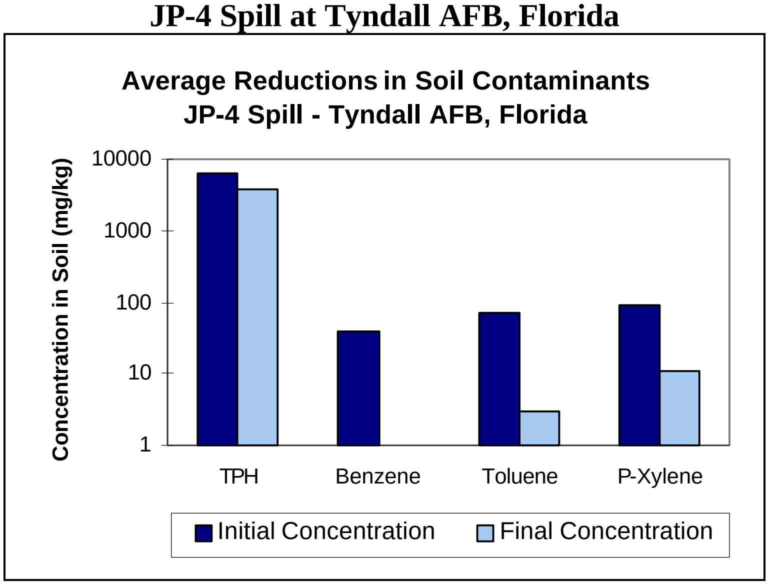
Figure 4-8. Initial Biodegradation Rates: Bioventing Initiative Project



BTEX Versus TPH Removal

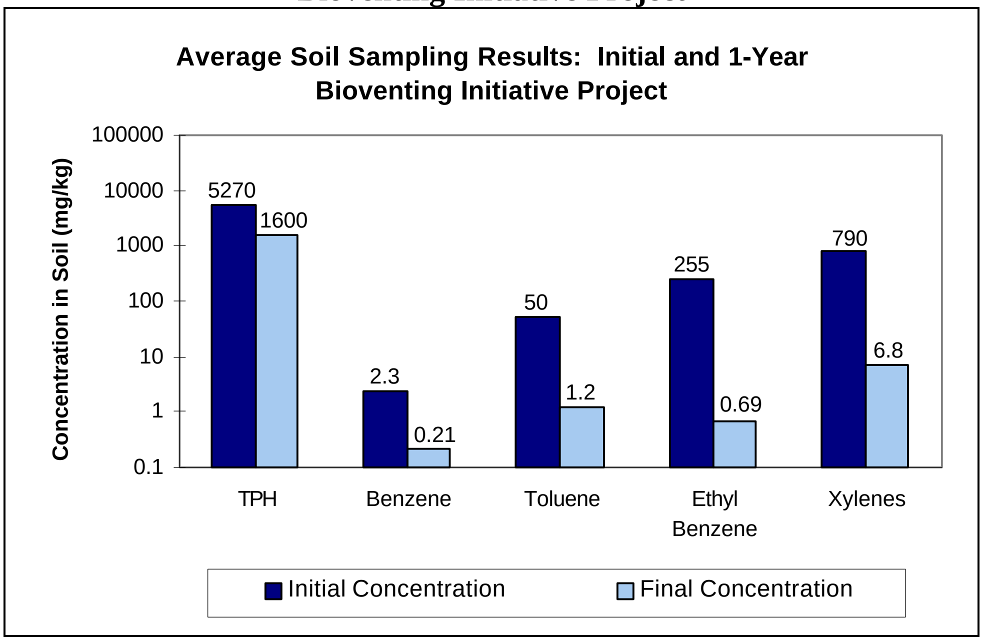
Due to their mobility and toxicity, BTEX generally are the compounds that are regulated the most stringently. Typically, these compounds degrade very rapidly during bioventing, and at most of the Bioventing Initiative sites, degraded to below detection limits within 1 year of operation of a bioventing system. This trend was illustrated in a study at Tyndall AFB and has been confirmed at 33 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 nine months of bioventing, total petroleum hydrocarbons were reduced by 40 percent from the initial concentration. However, the low-molecular-weight compounds such as benzene, toluene, ethylbenzene, and xylenes were reduced by more than 90 percent (Miller, 1990). Figure 4-9 shows these results.

Figure 4-9. Average Reductions in Soil Contaminants: JP-4 Spill at Tyndall AFB, Florida



If a risk-based approach to site cleanup is used which focuses on removing the soluble, mobile, and more toxic BTEX constituents of fuel hydrocarbons, remediation times can be significantly reduced as indicated by the Tyndall AFB example. The ability of bioventing to preferentially remove benzene and other aromatics makes this technology well-suited for risk-based remediations. Figure 4-10 illustrates the average TPH and BTEX removal achieved in soils after 1 year of bioventing based on 39 samples at 16 Bioventing Initiative sites. This illustrates the preferential reduction in soil BTEX concentrations achieved after one year of bioventing.

Figure 4-10. Average Soil Sampling Results, Initial and 1-Year Conditions: Bioventing Initiative Project



Volatilization

One important advantage of bioventing is that it produces little or no release of hydrocarbons into the atmosphere. Surface flux testing was performed at five Bioventing Initiative sites to measure potential surface emissions. The estimated volatile hydrocarbon flux to the atmosphere and maximum initial soil gas hydrocarbon concentration at these sites is shown in Table 4-3. To date, the maximum surface emission that has been observed is 2.5 milligrams per day per square meter. Rates of biodegradation are typically 100 times greater than rates of volatilization from these sites. In some situations, such as shallow gasoline contaminated soil, air injection could produce unacceptable surface emissions. At these sites, short-term soil vapor extraction and vapor treatment were implemented to reduce high soil vapor concentrations before implementation of air injection.

Table 4-3. Results of Flux Monitoring: Bioventing Initiative Project

Base	Site Type	Air Injection Rate (scfm)	Screen Depth (ft)	Total Flux Estimate (g/day)	Initial Soil Gas TVH (ppmv)
Plattsburgh AFB, NY	Fire Training	13	10 to 38	200	8,400
Beale AFB, CA	Fire Training	30	10 to 25	70	4,800
Bolling AFB, DC	Diesel Spill	20	10 to 15	200	860
Fairchild AFB, WA	JP-4 Spill	15	5 to 10	150	29,000
McClellan AFB, CA	Diesel Spill	50	10 to 55	30	380

Other Studies

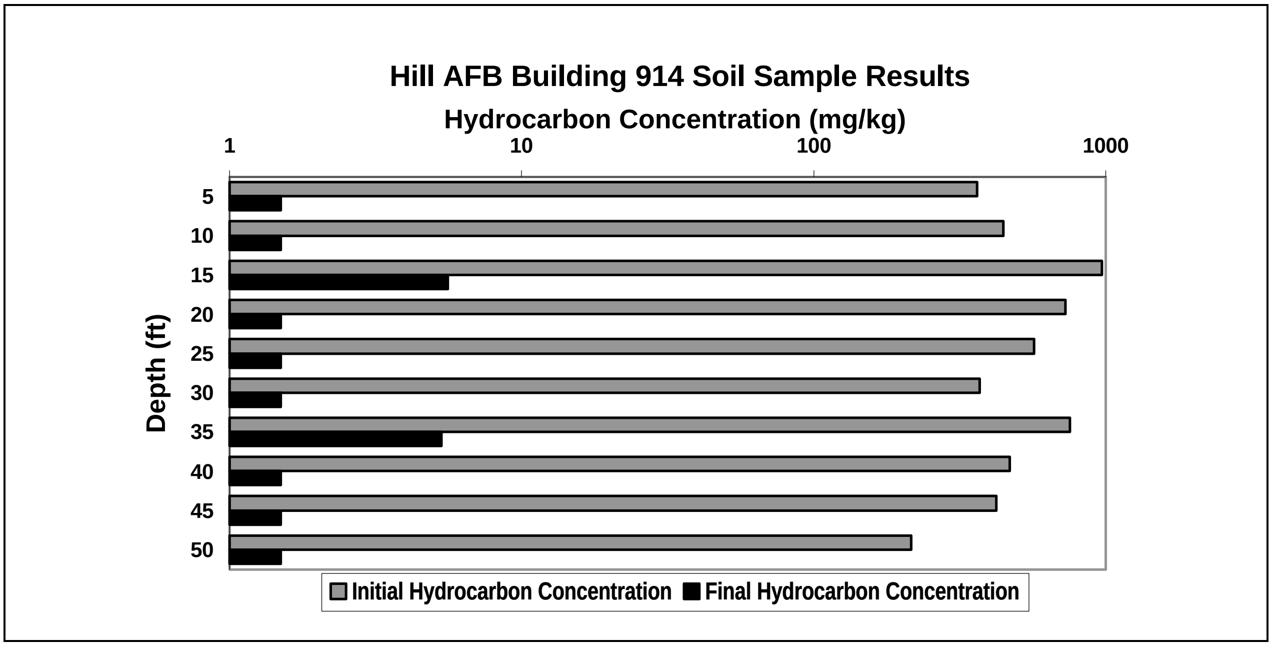
Several well-documented and long-term bioventing studies are presented below to illustrate significant results which have contributed to the Bioventing Initiative. The data are presented in Appendix A in the format recommended by the *Interagency Guide to Documenting Cost and Performance Information for Site Remediation Projects (Draft)* prepared by the Federal Remediation Technologies Roundtable (The Roundtable) Ad Hoc Work Group (The Work Group) on Cost and Performance Information (October 1994). The Roundtable, comprising several agencies including the USEPA, the USDOD, the U.S. Department of Energy (USDOE), and the U.S. Department of Interior, was created to exchange information on hazardous waste site remediation technologies and to develop strategies leading to a greater application of innovative technologies. The Work Group, consisting of representatives from government agencies, professional associations, and public interest groups, was created to determine which basic information would be practical and useful to report for documenting cost and performance information on remediation technologies. Both the DOD and the USEPA have efforts underway to document remediation projects using the recommended format.

The format recommended by the Work Group offers a coordinated and consistent collection of data sets to broaden the utility of the data, increase confidence in the future effectiveness of remedial technologies, and enhance the organization, storage, and retrieval of relevant information. The basic information types include waste characteristics and operating parameters that affect the cost or performance of different technologies, measurement procedures, standardized cost breakdown, and treatment technology performance. Standard terminology is used to allow a more meaningful comparison of technology performance, including assessments of potential presumptive remedies. Common terminology for waste management practices are derived from the Vendor Information System for Innovative Treatment Technologies (VISITT) and DOD's Installation Restoration Program (IRP). Other terminology is derived from USEPA's Superfund Land Disposal Restrictions (LDR) 6A/6B Guides, interagency Work Breakdown Structure (WBS), and the *Remediation Technologies Screening Matrix and Reference Guide* prepared jointly by the USEPA and the Air Force (July 1993). Standard Industrial Classification (SIC) Codes are used that best represent the historical activity responsible for the contamination at a site. Cost elements are given following a standardized WBS to allow greater comparability of costs among projects; this format will be used in the future as part of federal procurements for site remediation services.

Hill AFB Utah, Building 914 Site

A spill of approximately 25,000 gallons of JP-4 contaminated soils to a depth of approximately 60 feet. Soils are predominantly fine sands with occasional clay stringers. Regional groundwater is over 600 feet deep, and average soil moisture is less than 6 percent. A full-scale soil vapor extraction system was originally installed at the site. This 15-well system operated for 9 months until extracted vapors reached an asymptotic concentration and was then converted into a bioventing system by reducing extraction rates by over 70 percent. The system was operated in the bioventing mode for an additional 9 months, saving over $54,000 in off-gas treatment costs. During extraction, concentrations of oxygen, carbon dioxide, and hydrocarbons were monitored in the off gas. Based on these data, an estimated 110,000 pounds of fuel were volatilized, and 90,000 pounds were biodegraded during the total 18-month demonstration. Initial soil samples showed JP-4 concentrations as high as 20,000 mg/kg, with an average of approximately 400 mg/kg. Soils were resampled after the initial 9 months of vapor extraction, and again after 9 months of bioventing. Figure 4-11 illustrates the 98-percent reduction in fuel contamination achieved during the 18-month demonstration. Following this demonstration, the State of Utah approved closure of the site. See Tables A-1a through A-1e (Appendix A) for the Work Group Cost and Performance Information that was previously referenced.

Figure 4-11. Untreated and Treated Contaminant Concentrations. Hill AFB, Utah: Building 914 Site.

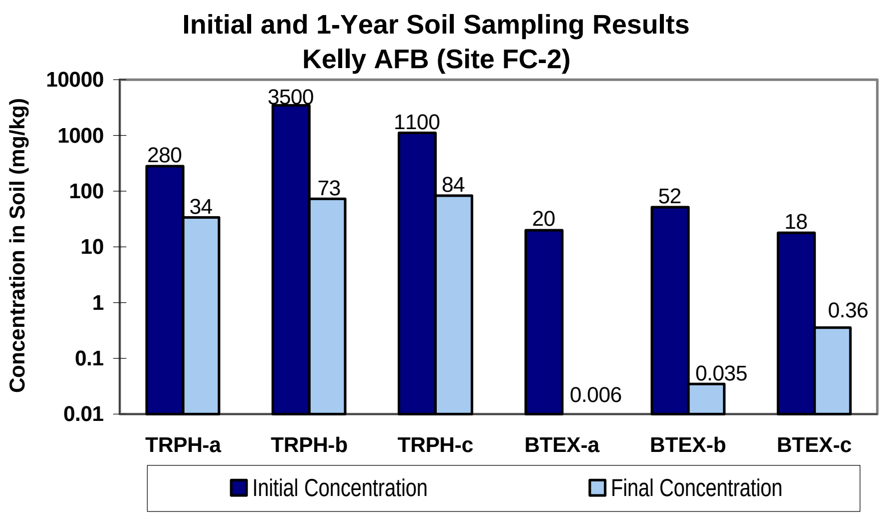


Note: each bar represents 14 or more averaged analytical results from the specified depth interval.

Kelly AFB, Site FC-2

This site was used from the 1950s to 1981 for fire training exercises. Waste petroleum, oil, and lubricant (POL) and fuel fires were set and extinguished around a simulated airplane at the center of the site two to four times a year. No containment system was used to prevent direct infiltration of POL and fuel into the soils, which are comprised of gravelly clay. Groundwater occurs between 15 and 18 feet below the ground surface. A single air injection well and four vapor monitoring points were installed at the site in December 1992. An air injection rate of approximately 48 standard cubic feet per minute (scfm) produced a radius of oxygen influence of at least 35 feet. An average initial biodegradation rate of 5,600 mg fuel per kg soil per year was estimated based on test results. Several soil and soil-gas samples were collected after one year of bioventing treatment. Figure 4-12 illustrates the removal of BTEX and TRPH from soils achieved to date. Due to the low concentrations of BTEX remaining in these soils, they are no longer a source of significant groundwater contamination. See Tables A-2a through A-2e (Appendix A) for the Work Group Cost and Performance Information that was previously referenced.

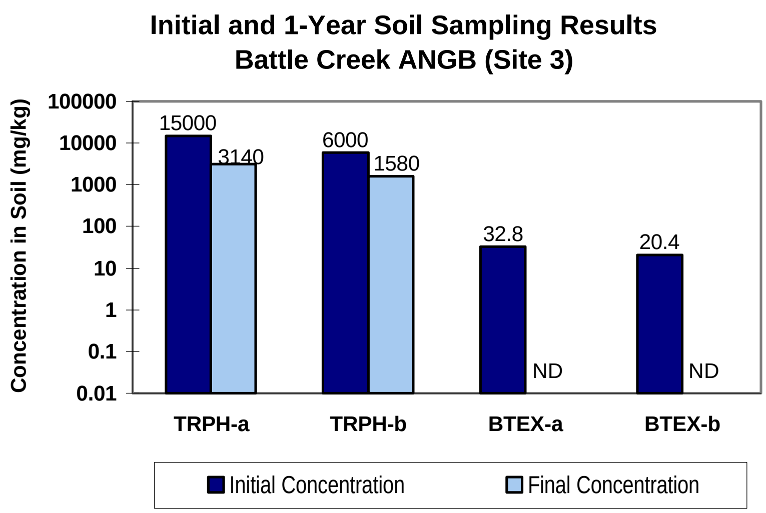
**Figure 4-12. Untreated and Treated Contaminant Concentrations.
Kelly AFB, Texas: Site FC-2.**



Battle Creek Air National Guard Base (ANGB) Michigan, Fire Training Area

An estimated 74,000 gallons of JP-4 jet fuel, waste oils, and hydraulic fluids were burned during training exercises at this abandoned fire training pit. Because the pit was unlined, significant quantities of these hydrocarbons have contaminated the predominantly sandy soils down to groundwater, which occurs at a depth of 30 feet. A single air injection well and three vapor monitoring points were installed at the site in September 1992. Air was injected at a rate of 40 scfm and produced a radius of oxygen influence of over 50 feet within 2 hours. This treatment radius encompassed the entire fire training pit, and Battle Creek ANGB personnel are continuing to operate the system for full-scale remediation. Initial biodegradation rates up to 3,700 milligrams of hydrocarbon per kilogram of soil per year were estimated. Several soil and soil-gas samples were collected after 1 year of bioventing treatment. Figure 4-13 illustrates the removal of BTEX and TRPH achieved to date. Due to the low concentrations of BTEX remaining in these soils, they are no longer a source of groundwater contamination, and site closure is now a viable option. See Tables A-3a through A-3e (Appendix A) for the Work Group Cost and Performance Information that was previously referenced.

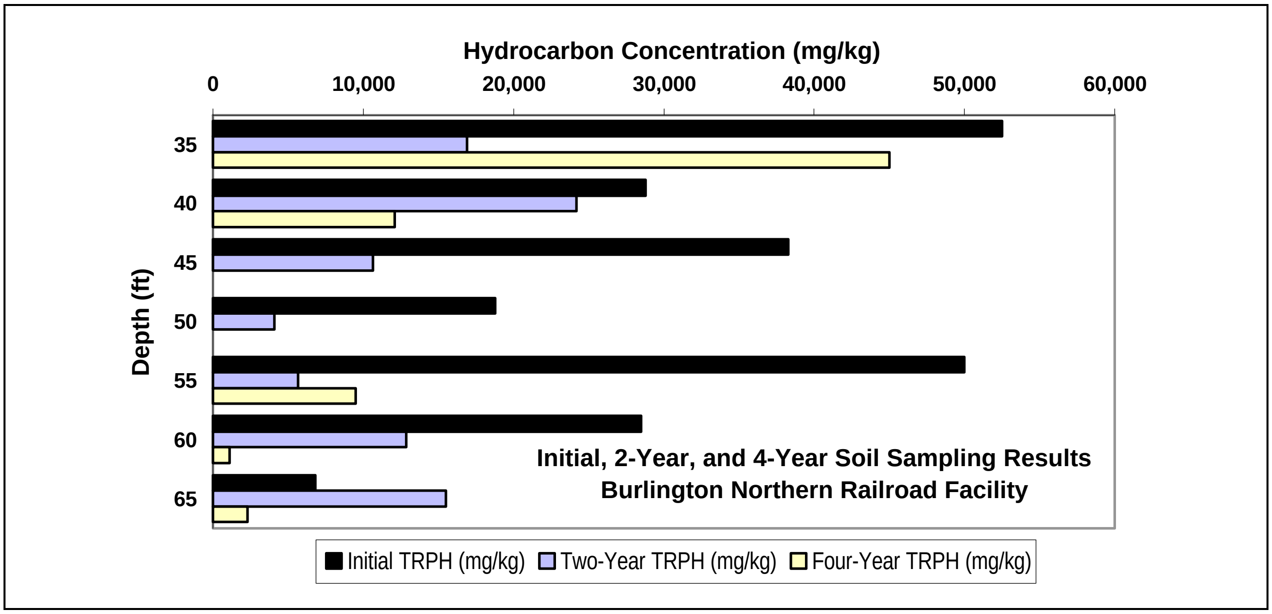
Figure 4-13. Untreated and Treated Contaminant Concentrations. Battle Creek ANGB, Michigan: Fire Training Area.



Burlington Northern Railroad Facility, Nebraska

An estimated 60,000 gallons of No. 2 diesel fuel was released from a ruptured pipe at a fueling pump house and contaminated an estimated 15,000 cubic yards of soil to a depth of approximately 65 feet. The Nebraska Department of Environmental Control (now the Nebraska Department of Environmental Quality) requested a remedial action plan to treat the diesel-contaminated soils to protect local groundwaters. Initially, a bioventing pilot test was implemented to determine soil properties (air permeability) and to assess the potential for partial volatilization and long-term biodegradation of diesel residuals. Initial testing estimated a biodegradation rate of 2,300 mg fuel/kg soil/year, and pilot testing confirmed that full-scale bioventing was feasible. A full-scale bioventing system was installed in September 1991, and has operated continuously for over four years. This system has eliminated the need for treatment of extracted vapors because of the low flow rates used and the nature of the fuel residuals being treated. Based on average respiration rates measured throughout system operation, the average biodegradation rate at the center of the spill has been as high as 4,800 mg fuel/kg soil/year. Gaseous anhydrous ammonia was injected at one vapor monitoring point to examine its mobility in the soil matrix, and an aqueous solution of ammonium nitrate fertilizer was added at other vapor monitoring points. An evaluation of monitoring results indicate that moisture and nutrient addition have enhanced biological degradation rates, although the nutrients are not highly mobile in the subsurface and are difficult to distribute uniformly throughout contaminated soils. Soil samples were collected in November 1993 and September 1995 to accurately assess remediation progress after approximately 2 and 4 years of system operation. Figure 4-14 illustrates the general reduction in diesel concentrations from initial site conditions. An overall TRPH reduction of 75 percent has occurred over the past 4 years of bioventing. Only the 35-foot depth interval showed an apparent increase in fuel concentrations, which is likely caused by the non-uniform distribution of contamination in the interbedded zone at this depth. Based on an estimated contaminated soil volume of 15,000 cubic yards, the total cost to date of bioventing at this site has been less than $10 per cubic yard. See Tables A-4a through A-4e (Appendix A) for the Work Group Cost and Performance Information that was previously referenced.

Figure 4-14. Untreated and Treated Contaminant Concentrations. Burlington Northern Railroad Facility, Nebraska: Fueling Pump House.

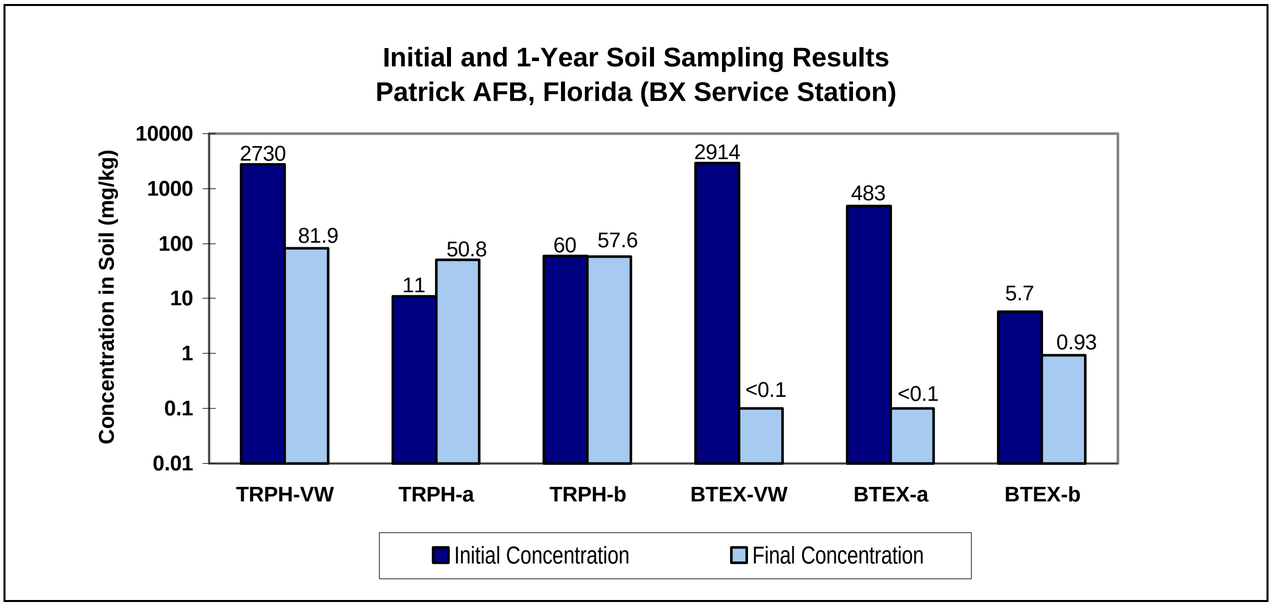


Note: All two-year samples represent an average of 2 or more sample locations per depth.

Patrick AFB, BX Service Station

Releases from USTs and fuel lines at a gasoline service station resulted in soil contamination from gasoline. TRPH concentrations in soil initially were found up to 2,730 mg/kg, and groundwater (water table at approximately 5 feet bgs) was also impacted by the releases. In March 1993, a bioventing pilot test was initiated with the installation of a horizontal vent well and three vapor monitoring points. Pilot test activities, including soil gas sampling, air permeability testing, radius of oxygen influence determination, and *in situ* respiration testing, indicated that bioventing would be an applicable technology at this site. However, high volatile organic compound (VOC) concentrations in the soil gas, ranging up to 100,000 ppmv, prohibited air injection even at low flow rates. Therefore, bioventing with air extraction was initiated in October 1993. Treatment of the offgas was necessary and was implemented with an internal combustion engine (ICE). The ICE provided both the vacuum to the vent well and removed VOCs from the offgas. Destruction of BTEX and TVH in the offgas was greater than 99 percent on average, and the offgas VOC concentration was reduced to below 5,000 ppmv in approximately 3 months. At this time, low flow rate extraction was continued with offgas treatment provided by biofiltration methods. After an additional 2 months of air extraction and offgas treatment, soil gas concentrations of VOCs were reduced to below 1,500 ppmv. The system was then reconfigured for low flow rate air injection for the remainder of the 12 month pilot testing period. Soil and soil-gas samples were collected after 12 months of testing and indicated that bioventing was effectively removing fuel hydrocarbons from the soil (Figure 4-15). See Tables A-5a through A-5e (Appendix A) for the Work Group Cost and Performance Information that was previously referenced.

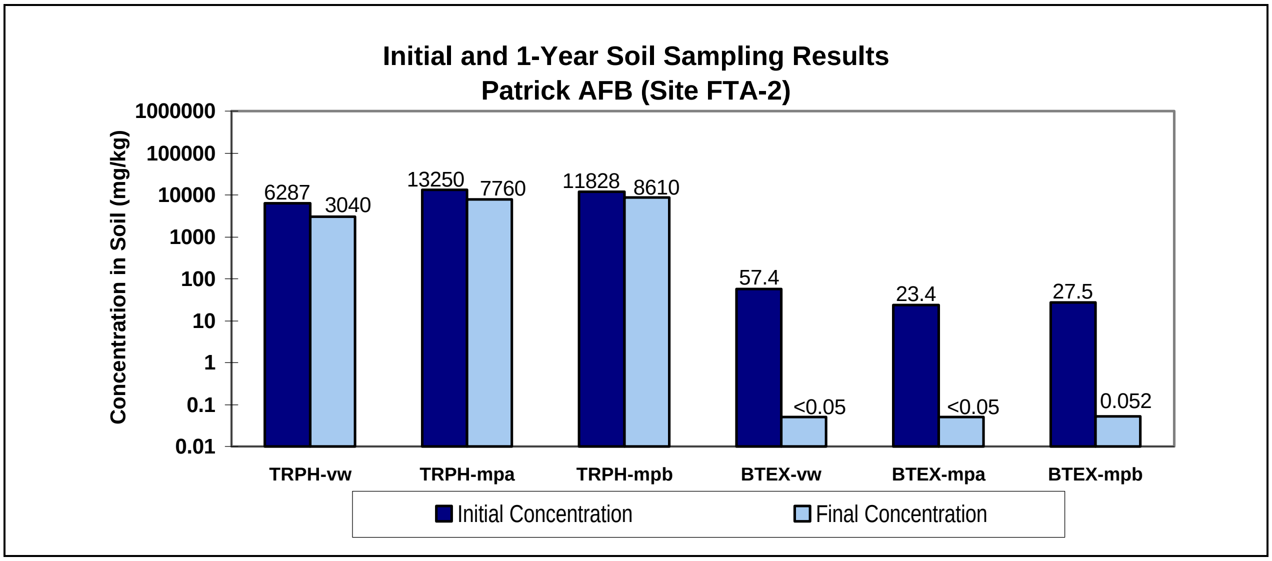
Figure 4-15. Untreated and Treated Contaminant Concentrations.
Patrick AFB, Florida: BX Service Station



Patrick AFB, Florida, Site FTA-2

Site FTA-2 is located adjacent to the Banana River (approximately 100 feet east) on Patrick AFB. The close proximity of this site to the Banana River posed a potential ecological risk to the area and was therefore selected as a high priority site. Site FTA-2 consists of an unlined, earth-bermed circular burn pit approximately 150 feet in diameter. The vadose zone is approximately 4 feet thick at this site, but fluctuates with the changing water table surface. The bermed area was used from 1963 to 1985 for fire control training exercises. A variety of combustible wastes (e.g., contaminated fuels and waste oils) were burned at the site until 1978, after which only uncontaminated fuels were used. Depth to groundwater at the site fluctuates between 3 to 6 feet bgs. Because of the shallow groundwater depths, a horizontal air injection vent well was installed in March 1993 at the site near the center of the burn pit along with five permanent soil vapor monitoring points. Single-depth monitoring point construction was used at the site with monitoring point screened intervals at 3.0 to 3.5 feet bgs. The blower and horizontal vent well at the site produced a long-term radius of oxygen influence of at least 30 feet. Based on oxygen utilization tests, fuel biodegradation rates at the site decreased from an average initial rate of 1,700 mg/kg/year to 1,100 mg/kg/yr over the 1-year test period. Soil and soil gas samples were collected before pilot testing and following 1 year of extended testing. Figure 4-16 illustrates the removal of BTEX and TRPH from soils achieved as a result of the bioventing pilot test. Actual fuel biodegradation rates at the site, as evidenced by initial and 1-year soil sample results, are 2 to 4 times those calculated using initial and 1-year oxygen utilization results. See Tables A-6a through A-6e (Appendix A) for the Work Group Cost and Performance Information that was previously referenced.

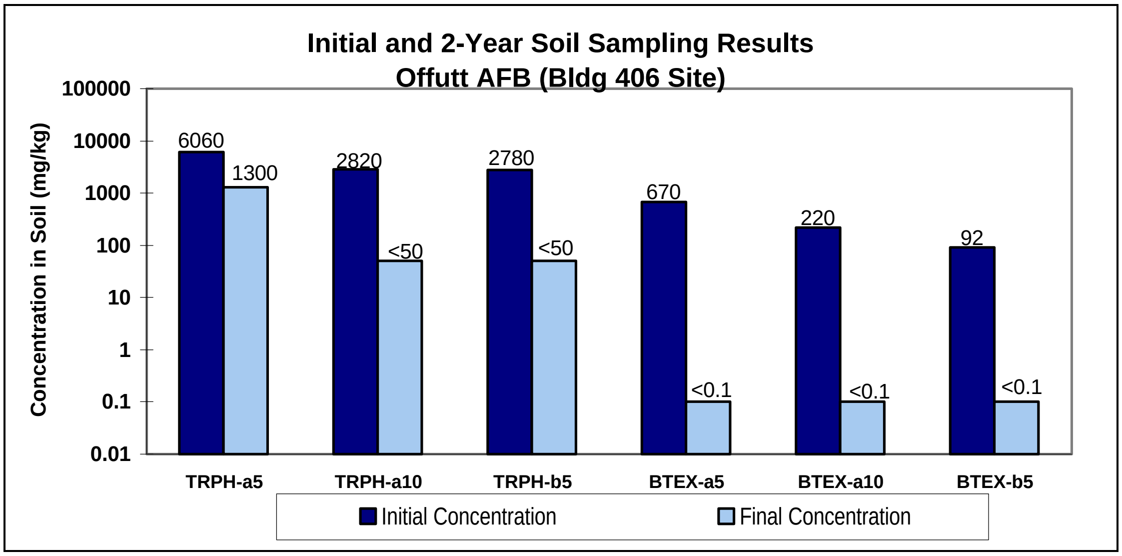
Figure 4-16. Untreated and Treated Contaminant Concentrations. Patrick AFB, Florida: Site FTA-2



Offutt AFB, Nebraska, Building 406 Site

Building 406 Site is the location of a former jet fuel pumphouse, piping, and 6 underground storage tanks (USTs). The USTs, each having a storage capacity of 50,000 gallons, most recently contained JP-4 jet fuel. The USTs and pumphouse were excavated and removed prior to installation of the pilot test bioventing system in October 1993. Prior to system installation, groundwater at the site was measured at a depth of approximately 15 feet below ground surface (bgs). Four air injection vent wells and three vapor monitoring points were installed. One vent well was installed in the corner of the excavation where the highest hydrocarbon concentrations were detected upon removal of the USTs. The other vent wells were installed in the three remaining corners of the excavation to fully oxygenate the entire area of the excavation. An air injection flow rate of 2.7 scfm per vent well produced a radius of oxygen influence of at least 30 feet. An average initial biodegradation rate of 13,700 mg fuel per kg soil per year was estimated based on initial testing results. However, subsequent testing showed this rate decreased during the initial 6-months of testing to an average of 1,000 mg/kg/yr. AFCEE and the Nebraska Department of Environmental Quality agreed to jointly fund an additional year of testing and sampling. Therefore, respiration tests were performed initially and at 6, 12, 18, and 24 months. Soil and soil gas sampling was performed initially and after 12 and 24 months of system operation. Extensive soil sampling was performed at this site. Initially 12 soil samples were collected and 16 soil samples were collected after 12 and 24 months of testing. Figure 4-17 illustrates the removal of BTEX and TRPH from soils achieved to date. See Tables A-7a through A-7e (Appendix A) for the Work Group Cost and Performance Information that was previously referenced.

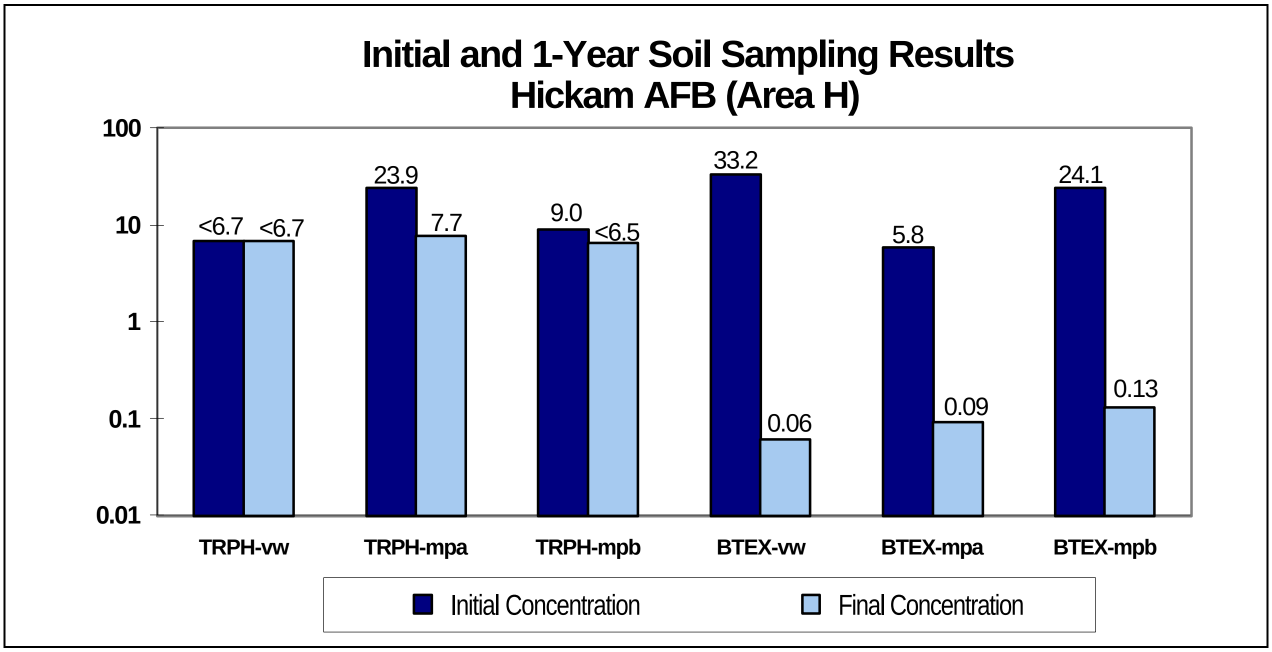
Figure 4-17. Untreated and Treated Contaminant Concentrations. Offutt AFB, Nebraska: Building 406 Site



Hickam AFB, Hawaii, Area H

Area H is located on the main installation at Hickam AFB and overlies an aquifer where long-term fuel leaks from several pipelines have created a very large fuel plume in groundwater beneath the site. Investigations in 1985 found portions of the plume having over 6 feet of apparent free product. Area H represents only one portion of the total fuel contaminated area which originally extended beneath approximately 40 acres of the base. Fuel contamination at Area H is highly volatile aviation fuel, present in the vapor phase, and also in free phase at the groundwater table and in seams and fractures in the vadose zone formation. The geology at the site consists of clay, sand, and coralline rubblestone to a depth of approximately 5 feet bgs, underlain by volcanic tuff. The tuff is relatively impermeable, but has fractures or seams in which fuel contamination preferentially collects. A bioventing system composed of one air injection vent well and 3 soil vapor monitoring points was installed at the site in March 1993. At the time of installation, groundwater was encountered at approximately 20 feet bgs and heavily contaminated soils were encountered below 16 feet bgs. During initial pilot testing the volcanic tuff at Area H was found to be fairly impermeable, but injected air was able to move through the formation via fractures and seams. Fuel biodegradation rates decreased during the 1-year test from an initial average of 110 mg/kg/year to less than 10 mg/kg/year. Figure 4-18 illustrates the removal of BTEX and TRPH from soils achieved as a result of the bioventing pilot test. See Tables A-8a through A-8e (Appendix A) for the Work Group Cost and Performance Information that was previously referenced.

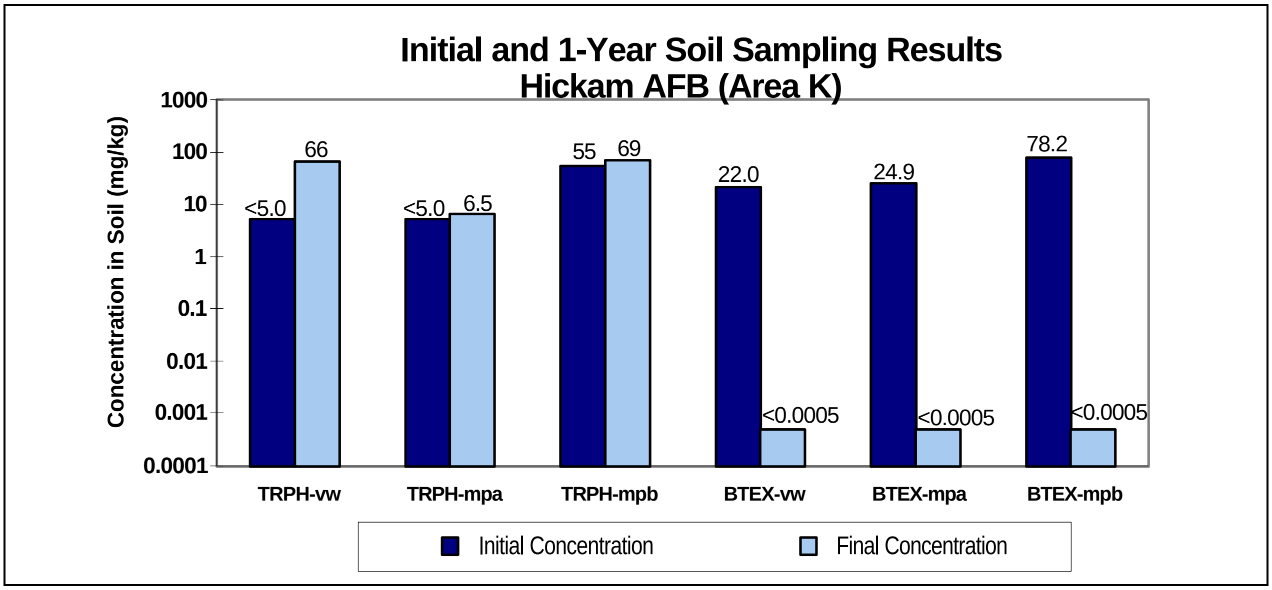
Figure 4-18. Untreated and Treated Contaminant Concentrations. Hickam AFB, Hawaii: Area H



Hickam AFB, Hawaii, Area K

Area K is located on the main installation at Hickam AFB, adjacent to a nine-hole golf course. A large free product plume under the site may have been the result of long-term fuel leaks from a JP-4 jet fuel pipeline near the site. Fuel contamination at Area K is highly volatile aviation fuel, present in the vapor phase, and also in free phase at the groundwater table and in seams and fractures in the vadose zone formation. Free product thickness beneath the site measured as much as 1 foot during 1985 investigations. A pilot-scale bioventing system including one air injection vent well and three vapor monitoring points was installed in March 1993. Heavily contaminated soils were encountered in a "smear zone" below 4.5 feet bgs and groundwater was encountered at 9 feet bgs. Fuel biodegradation rates decreased during the 1 year bioventing pilot test from an initial average of 3,400 mg/kg/year to a final average of 1,200 mg/kg/year. Figure 4-19 illustrates the removal of BTEX from soils achieved as a result of the bioventing pilot test. The apparent increase in TRPH concentrations is an artifact of sampling due to heterogeneity of the soils. See Tables A-9a through A-9e (Appendix A) for the Work Group Cost and Performance Information that was previously referenced.

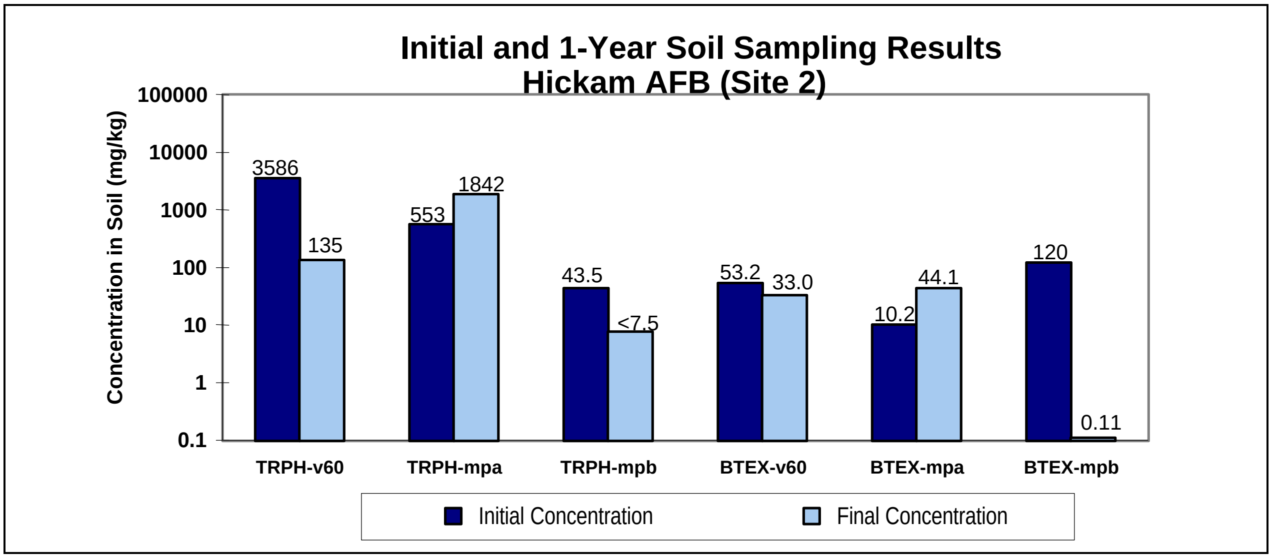
Figure 4-19. Untreated and Treated Contaminant Concentrations. Hickam AFB, Hawaii: Area K



Hickam AFB, Hawaii, Site 2

Site 2 (since renamed Site ST12) is located at the Waikakalaua Fuel Storage Annex (FSA) approximately 10 miles northwest of the main Hickam AFB installation. An open-bottomed disposal basin at the site was formerly used for the disposal of waste petroleum products at the FSA. Lithology at Site 2 is composed of shallow deposits of clay and silt to approximately 25 feet bgs underlain by saprolite (weathered basalt). The saprolite extends from approximately 25 to 110 feet bgs. The saprolite is underlain by weathered, fractured basalt, and basal groundwater is found in the basalt at approximately 700 feet bgs. The primary contaminants at the site are petroleum hydrocarbons present in the vadose zone. During installation of the pilot-scale system in March and April 1993, elevated concentrations of petroleum hydrocarbon contaminants were detected in soil samples at depths below the disposal basin bottom (greater than 20 feet bgs). The original pilot-scale system, which has since been expanded, was composed of one air injection vent well and three vapor monitoring points. The pilot-scale vent well extends to a depth of approximately 101 feet bgs with screened intervals between approximately 15 and 45 feet bgs and 65 and 100 bgs. The well is cased from 45 to 65 feet bgs to prevent the intrusion of perched water, which was encountered from 52 to 57 feet bgs. Results from initial pilot testing indicated that a radius of oxygen influence of approximately 40 feet could be achieved in intermediate-depth soils (20 to 40 feet bgs) at the site. Figure 4-20 illustrates the removal of BTEX and TRPH from soils achieved as a result of the initial 1-year bioventing pilot test. The pilot-scale system was expanded in November 1995. The expanded-scale system includes two additional vent wells (one new vent well and one converted groundwater monitoring well) and an additional vapor monitoring point. See Tables A-10a through A-10e (Appendix A) for the Work Group Cost and Performance Information that was previously referenced.

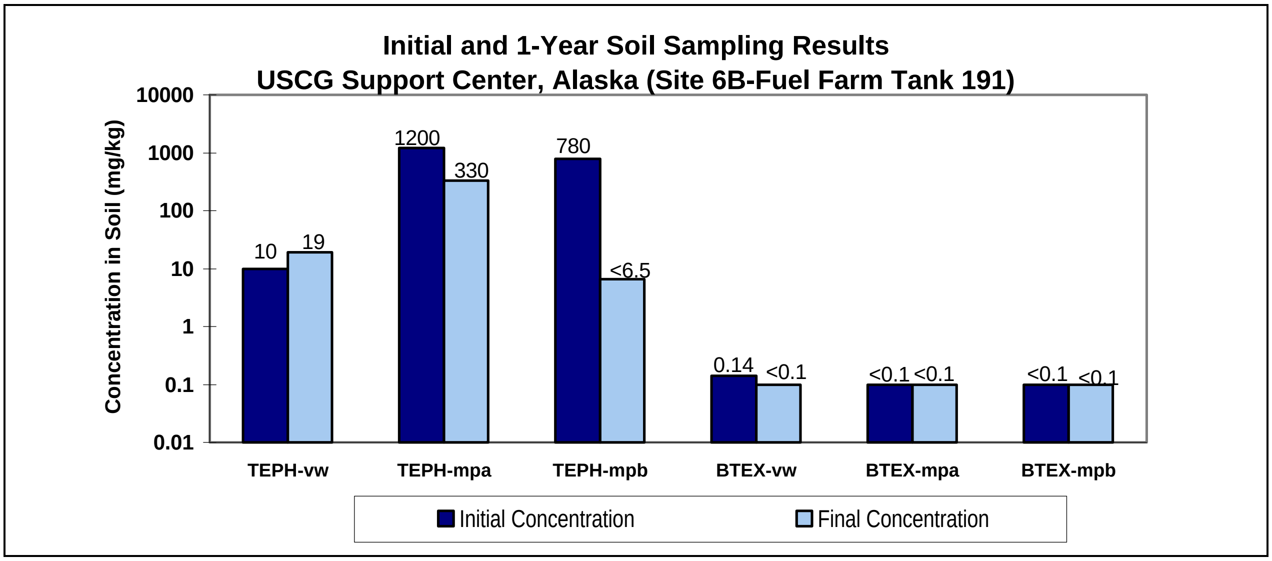
Figure 4-20. Untreated and Treated Contaminant Concentrations. Hickam AFB, Hawaii: Site 2



US Coast Guard Support Center Kodiak, Alaska, Site 6B-Fuel Farm (Tank 191)

Site 6B contains 13 large above- and underground storage tanks (USTs) that were constructed beginning in 1942. Tank 191 is an inactive, concrete and steel, 567,000-gallon UST. The dates of installation and operation are uncertain. Tank 191 previously was used for storage of diesel and JP-5 jet fuel. Leakage from Tank 191 was reported to be 500 gallons per day in 1954 and by one account and 2,300 gallons per day in the mid 1950's by another. It was reported that the tank was "secured" in the mid 1950's and was abandoned in 1978. The tank was constructed in an excavation that extended into the slate bedrock. Natural surface soils consist of silt and clay-rich glacial tills, however, the pilot test was performed in the sand and gravel fill that surrounds the tank. An artificial aquifer has been created around the tank due to the excavation into the slate bedrock. Groundwater was encountered at approximately 15 feet bgs during system installation and appeared to be less than 10 feet bgs during the 1-year testing event. One air injection vent well and two vapor monitoring points were installed in August 1994. Existing groundwater monitoring wells were also utilized for pilot testing. An air injection flow rate of 26 standard cubic feet per minute (scfm) produced a radius of oxygen influence of 90 feet in deeper soils within the fill surrounding the tank. An average initial biodegradation rate of 2,400 mg fuel per kg soil per year (mg/kg/yr) was estimated based on test results. Soil and soil gas samples were collected prior to pilot testing and after 1 year of extended testing. Figure 4-21 illustrates the removal of BTEX and TEPH from soils achieved as a result of the 1-year pilot test. See Tables A-11a through A-11e (Appendix A) for the Work Group Cost and Performance Information that was previously referenced.

**Figure 4-21. Untreated and Treated Contaminant Concentrations.
US Coast Guard Support Center, Kodiak, Alaska:
Site 6B-Fuel Farm (Tank 191)**



Section 5
APPLICABLE OR RELEVANT AND APPROPRIATE REQUIREMENTS (ARARs)

Section 121(d)(2)(A) of CERCLA specifies that Superfund remedial actions must meet any federal standards, requirements, criteria, or limitations that are determined to be legally "applicable" or "relevant and appropriate" requirements (ARARs). It also specifies that state ARARs must be met if they are more stringent than federal requirements. These so-called CERCLA-121 requirements generally apply as a matter of law only to remedial actions, except when removal actions involve the transfer of a hazardous substance, pollutant, or contaminant off site. However, the NCP requires that ARARs be identified and attained to the extent practicable for removal actions (40 CFR 300.415[I]).

ARAR Categories

ARARs are generally placed in three categories: chemical-specific, action-specific, and location-specific. In evaluating the attainment of ARARs, the Air Force installations will take into consideration the cumulative impact from all related activities.

Three categories of ARARs:

- *Chemical-specific ARARs define cleanup levels in the ambient environment*
- *Action-specific ARARs define performance and design standards for the action taken*
- *Location-specific ARARs modify chemical-and/or action-specific ARARs to reflect the unique requirement of the location*

Chemical-Specific ARARs

Chemical-specific ARARs set limits on concentrations of specific hazardous substances, pollutants, and contaminants in the environment where removal actions are being applied. These ARARs are applied to the chemical of concern in the designated media. Currently, there are no promulgated federal or state chemical-specific concentrations for fuel-hydrocarbons in soils. However, ARARs in air, surface water, and groundwater may play a significant role in decisions involving the remediation of fuel-hydrocarbons in soils. Many fuel-hydrocarbons, especially BTEX components of fuels, are generally considered to be mobile, and they may migrate from soils to air and water. Therefore, the need for remediation and the establishment of soil cleanup goals for fuel hydrocarbons should take into consideration ARARs in other media, using an appropriate fate and transport model. Of potential concern is the potential impact on groundwater.

Action-Specific ARARs

Action-specific ARARs set controls or restrictions on activities related to the management of hazardous substances or pollutants. Key action-specific ARARs for bioventing removal actions would generally come into play for bioventing systems in the extraction mode, because vapor treatment would need to be considered usually following rules promulgated by state and local rules.

Location-Specific ARARs

Location-specific ARARs establish additional restrictions on contaminant levels or activities in the environment and are triggered by the unique nature of site location or its immediate environment. They may function as chemical-specific ARARs or action-specific ARARs. Examples of locations that require special consideration include floodplains, wetlands, historic places, and sensitive ecosystems or habitats. If the proposed site for bioventing removal action is located in or near any of these locations, precautions need to be taken to ensure the compliance of the appropriate location-specific ARARs to the maximum extent practicable.

Risk-Based Corrective Action (RBCA)

Recently, the American Society of Testing and Materials (ASTM) finalized development of a guide entitled *Standard Guide for Risk-Based Corrective Action Applied at Petroleum Release Sites (E 1739-95)* (ASTM, 1995). The ASTM guide establishes a framework for conducting corrective action at petroleum release sites. This new and innovative framework represents a paradigm shift over previous corrective action methodologies. In the past, most corrective action methodologies have been based on achieving generic health-based or technology-based cleanup goals. Risk-based corrective action, otherwise known as RBCA or “Rebecca”, has been developed to provide a technically defensible, consistent, multi-tiered, exposure/risk-based assessment methodology, which provides a strong basis for site specifically determining site classification and initial response, cleanup goals, and corrective action for soil and groundwater. Most importantly, the RBCA framework is protective of human health and the environment, while being practical and cost effective. The American Petroleum Institute (API) has developed a computer application, entitled Decision Support Software (DDS), to automate and standardize their version of the process.

EPA’s Office of Underground Storage Tanks (OUST) issued an “open letter” to federal and state UST program staff and state fund managers, embracing RBCA as one technique to streamline corrective action. For these regulators, RBCA provides a decision-making framework that allows them to take into account not only the potentially harmful effects of contaminants associated with UST system releases, but also the site-specific factors that influence the extent to which human health and environmental receptors may be exposed to those contaminants. These factors can then be incorporated into their corrective action decisions and management strategies, which include establishing site-specific cleanup goals, establishing requirements for responsible parties, determining how much corrective action oversite is necessary, and determining what, if any, further remedial action is necessary.

The Model ASTM “Tiered” Approach:

- ***Tier 1*** *- Entails a qualitative risk assessment that is based on general site assessment information. Helps categorize sites and determines acceptable time frames for corrective action, if necessary.*

- ***Tier 2*** *- Calls for the collection of more site-specific data to determine appropriate risk-based actions. Sets conservative corrective action objectives that are protective of human health and the environment.*

- ***Tier 3*** *- Focuses completely on site-specific conditions. More sophisticated mathematical descriptions of fate and transport phenomena are used and descriptions of a range of possible exposures/risks are generated. Site-specific risk assessment models may be developed.*

The ASTM E 1739-95 Guide is based on a tiered approach to risk and exposure assessment, where successive tiers call for increasingly sophisticated levels of data collection and analysis. The goal of all tiers is to achieve similar levels of protection for human health and the environment. The difference among tiers is that, in moving to higher tiers, corrective action can become more efficient and cost-effective because the conservative assumptions of earlier tiers are replaced with more realistic site-specific assumptions. The 3-tiered RBCA approach serves only as a framework that users, and states in particular, can use to evolve their own UST corrective action making program. Texas, for example, has developed a risk-based approach that entails site classification which is based on site similarity to specific exposure scenarios, and sites fall into one of four classes. Ohio's risk-based approach to corrective action uses four tiers of risk assessment.

Specific Laws and Regulations for Compliance

Bioventing removal actions will comply with all Federal, State, and/or local environmental laws and regulations. Since Air Force installations where bioventing removal actions will be implemented are located throughout the United States, it is beyond the scope of this General Evaluation Document to address all potential State and local laws and regulations that may be applicable. Therefore, the following is a list of the most important Federal environmental laws and regulations that may serve as ARARs for bioventing removal actions.

- Occupational Safety and Health Administration (OSHA) regulations
- Department of Transportation (DOT) regulations
- National Environmental Policy Act (NEPA)
- Clean Water Act (CWA)
- Clean Air Act (CAA)
- Endangered Species Act (ESA) of 1973 (16 USC 1531 et seq.); 50 CFR Parts 200 and 402
- Toxic Substances Control Act (TSCA)
- Resource Conservation and Recovery Act (RCRA), as amended by the Hazardous and Solid Waste Amendments (HSWA)
- Comprehensive Environmental Response Compensation and Liabilities Act (CERCLA) as amended by the Superfund Amendments and Reauthorization Act (SARA)
- National Oil and Hazardous Substances Contingency Plan (NCP), 40 CFR 300
- National Historic Preservation Act Section 106 (16 U.S.C. 470 et seq.); 36 CFR Parts 800 and 60
- Archaeological and Historic Preservation Act (16 USC Section 469 to 469c-1); 36 CFR Part 65
- Fish and Wildlife Coordination Act (16 USC 661 et seq.); 40 CFR 6.302

Guidance Documents

Bioventing removal actions will conform to the maximum extent practicable to the applicable requirements of the most current version available of the following guidance documents.

- Test Plan and Technical Protocol for a Field Treatability Test for Bioventing, prepared for the US Air Force Center for Environmental Excellence (AFCEE), May 1992.
- 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, prepared for the US Air Force Center for Environmental Excellence, February 1994.
- Principles and Practices of Bioventing (Volume I: Bioventing Principles; Volume II: Bioventing Design) (Leeson and Hinchee, 1995).
- Guidance for Oversight of Remedial Designs and Remedial Actions Performed by Potentially Responsible Parties, Interim Final US Environmental Protection Agency (EPA)/540/G-90/001; EPA Office of Solid Waste and Emergency Response (OSWER) Directive 9355.5-01, April 1990.
- Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA (OSWER Directive 9335.3-01), 1988.
- Risk Assessment Guidance and Superfund, Volume 1, Human Health Evaluation Manual (Part A), Interim Final (EPA/540/1-89/002), 1989.
- Risk Assessment Guidance and Superfund, Volume 2, Environmental Evaluation Manual, Interim Final (EPA/540/1-89/001), 1989.
- Standard Guide for Risk-Based Corrective Action Applied at Petroleum Release Sites, ASTM Standard E 1739-95.
- Test Methods for Evaluating Solid Waste (SW-846), Third Edition (1986), and 1987 updates.
- Guidance on Remedial Action for Contaminated Groundwater at Superfund Sites (OSWER Directive 9283.1-2), 1988.
- A Compendium of Superfund Field Operation Methods, (EPA/540/P-87/001; OSWER Directive 9335.0-14), December 1987.
- Uniform Building Code.
- National Fire Protection Association Standards.
- Air Force Manual (AFM) 86-2, Standard Facility Requirements (Interim Draft, January 1986).
- Air Force Regulation (AFR) 88-15; Criteria and Standard for Air Force Construction.
- AFM 88-29, Engineering Weather Data, 1 July 1978.
- Federal Accessibility Standards.
- Air Force Engineering Technical Letters (AF ETLs).
- American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE) Handbooks; Fundamentals, Systems, Equipment, and Applications.
- National Standard Plumbing Code.

Section 6
SITE SELECTION METHODOLOGY

In order to select candidate sites for the application of bioventing as the presumptive remedy, two decisions need to be made:

- *Whether or not a removal action is warranted at the site*
- *Whether or not site conditions will allow bioventing to be effective in removing contaminants from the vadose zone*

To apply bioventing, a removal action must be necessary and bioventing must be technically feasible. A bioventing feasibility evaluation serves as an initial screening for sites that can be successfully treated with this technology. A removal action evaluation is used to qualify, and perhaps prioritize, sites for the need of a removal action. The sequence of these evaluations is not important, and they may even proceed in parallel. However, both evaluations must result in affirmative responses for the bioventing presumptive remedy to be put in effect. Figure 6-1 is a decision tree for determining the potential applicability of bioventing at a site and focuses on site conditions. Each of the components shown in Figure 6-1 are discussed in this section.

In order for the bioventing process to be effective, the contaminants must be able to be biodegraded, and the soil matrix must be permeable enough to allow oxygen via air to be delivered to the soil contamination. In practical terms, these constraints require that the contaminants be biodegradable by venting the soil with air. For this to work, site characteristics must match certain requirements related to soil bacteria and nutrients, physical soil properties, and the nature of the contaminants themselves. These site characteristics must be verified through site characterization activities. The following subsections discuss site characteristic requirements for bioventing and site characterization activities.

Requirements for Bioventing

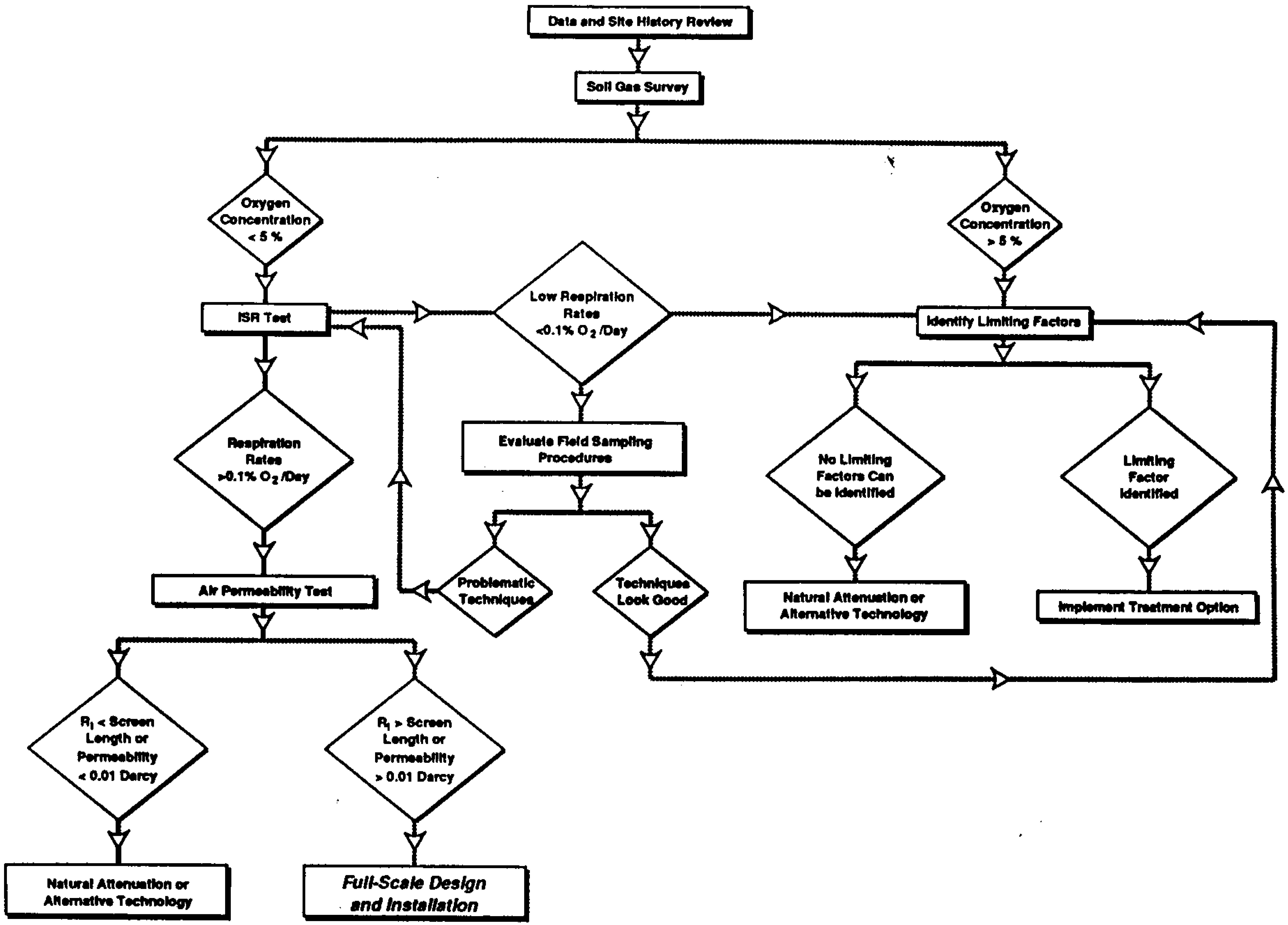
In evaluating the feasibility of bioventing to remediate contaminated soil at a particular site, known site conditions are compared to the necessary requirements for bioventing. The following is an assessment of these prerequisites.

The following are the main prerequisites for successful bioventing:

- *Established natural bacteria*
- *Available nutrients*
- *Soil moisture*
- *Air-filled porosity*
- *Adequate carbon source and fuel-hydrocarbon concentrations*
- *Oxygen*

FIGURE 6-1

DECISION TREE FOR DETERMINATION OF POTENTIAL APPLICABILITY OF BIOVENTING AT A SITE



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Established Natural Bacteria and Available Nutrients

Most soils have a sufficient natural baseline of hydrocarbon-degrading microorganisms. Because of this ubiquitous presence of natural microorganisms, plate counts or laboratory column tests do not appear to provide useful data for site selection. The presence of these are verified by baseline soil-gas sampling of initial oxygen and carbon dioxide concentrations (low oxygen and high carbon dioxide concentrations indicate microbial oxygen utilization and respiration). Such baseline field screening of soil gas oxygen and carbon dioxide has also been shown to be useful for indirectly detecting and delineating subsurface fuel contamination (Deyo et al., 1993). Field-scale *in situ* respiration (ISR) tests provide a more quantitative evaluation of the activity of hydrocarbon-degrading microorganisms (discussed later in this section).

Soils also usually have sufficient available nutrients to maintain biologic activity, which can be verified by soil-nutrient analysis for specific nutrients including nitrogen and phosphorous. Some researchers have suggested that available nitrogen may be present due to biological nitrogen fixation (Sorenson et al., 1991; Miller, 1990). Although an optimal Carbon : Nitrogen : Phosphorous (C:N:P) ratio of 250:10:1 may not be available, natural nutrient levels are sufficient to sustain some level of biological respiration when oxygen, the most limiting factor, is provided (Miller et al., 1993).

Bench-scale testing generally indicates increased biological activity after nutrient addition, but the benefits of such addition for in situ bioremediation systems has not been consistently demonstrated. Previous studies at Tyndall AFB (Florida) demonstrated that no significant benefit was derived from nutrient or moisture addition (Miller and Hinchee, 1990a and 1990b; Miller 1990; Miller et al., 1991; Sorenson et al., 1991). A major question to be addressed in ongoing and future research is whether or not sites with high natural nutrient levels exhibit higher long-term respiration than low-nutrient sites and whether the addition of nutrients would be cost-effective.

Soil Moisture and Air-Filled Porosity

Soil moisture is required for microorganisms to live. Increasing soil moisture will often enhance microbial activity (Hinchee and Arthur, 1990). Too much moisture can reduce the air permeability and air-filled porosity of the soil and decrease its oxygen-transfer capacity. However, the diffusion of oxygen during venting can be a significant mechanism for oxygen distribution to low-permeability zones, and some recent field studies have verified the effectiveness of bioventing in such soils (Downey et al., 1992; Phelps et al., 1995).

Adequate Carbon Source and Fuel Hydrocarbon Concentrations

The fuel hydrocarbons in a zone of soil contamination provide an adequate carbon source for cell production and respiration necessary to sustain microbial activity for biodegradation. When total fuel hydrocarbon concentrations are significantly reduced, biodegradation will continue but may be difficult to measure due to reduced oxygen utilization.

Oxygen Concentration in Soil Gas

An adequate concentration of oxygen in soil gas at a fuel-contaminated site is usually the main limiting factor for natural biodegradation to occur, since soils with significant fuel contamination are almost always oxygen depleted due to consumption by microorganisms. Therefore, venting the contaminated soil zone with air (20.8% oxygen) is implemented to sustain microbial activity. Initial oxygen concentrations in soil gas are measured prior to venting for baseline measurements.

Site Characterization Activities

Site characterization is an important step in determining the feasibility of bioventing and in providing information for a full-scale bioventing design. This subsection discusses site characterization methods that are recommended for bioventing sites based on extensive field experience and a statistical analysis of the Bioventing Initiative Project data (Leeson and Hinchee, 1995). These parameters address the requirements for bioventing as discussed above, and are the most useful in predicting the potential applicability of bioventing at a contaminated site. The sequence of events for site characterization of a typical site are discussed below.

Site characterization activities at a potential bioventing site should include the following:

- *Review of existing site data*
- *Soil gas survey*
- *Soil characterization*
- *Initial Pilot Testing*
    - *In Situ Respiration (ISR) testing*
    - *Soil gas permeability testing*
    - *Radius of influence determination*

Existing Data and Site History Review

An initial review of site data will provide preliminary information for determining whether bioventing is a feasible option for a specific site. Also, the initial data review will help to identify any additional information that is needed to complete the bioventing design.

Information to be obtained during the data review should include the following:

- *Type of contaminants*
- *Quantity and distribution of free product (if present)*
- *Historic water table levels*
- *Three-dimensional distribution of contaminants*
- *Potential for a continuing source due to leaking pipes or tanks*
- *Particle size distribution or soil gas permeability*
- *Surface features such as concrete or asphalt*

If fuel is present as free product floating on the water table, removal before bioventing must be addressed because free product will act as a continuous source of contamination to groundwater and the vadose zone. Free product recovery is not always feasible despite its presence in site monitoring wells. A field recoverability test should be conducted according to established protocols such as those for bioslurping (Battelle, 1995), which is discussed in Section 8. If significant contamination is present below the water table, due to a fluctuating water table spreading contamination, dewatering may be needed to complete remediation, or bioventing during seasonally low water table elevations may be the only feasible approach.

Bioventing is only applicable to aerobically biodegradable contaminants, such as fuel hydrocarbons, but bioventing also may potentially be applied at some sites contaminated with both chlorinated solvents and petroleum hydrocarbons. An initial estimate of the three-dimensional distribution of contamination will provide a guideline for conducting a soil-gas survey, for collecting initial soil samples, and generating an initial estimate of the screen depths and size of the required bioventing system. Continuing sources of contamination such as leaking pipes must be repaired for bioventing to achieve cleanup. If available, particle size distribution can be used to estimate air permeability.

Soil Gas Survey

At sites where the contamination is at sufficiently shallow depths (<20 feet), a soil gas survey should be conducted initially to determine whether oxygen-limited conditions exist. Data on soil-gas concentrations of oxygen, carbon dioxide, and TPH can provide valuable insight into the extent of subsurface contamination, whether bacteria are present that are capable of degrading the contaminants of concern, the potential for *in situ* bioventing, and can assist in locating suitable areas for vent well and monitoring point placement. The soil-gas concentrations of these indicators in atmospheric air and uncontaminated background soils are compared to concentrations in the contaminated area. In a fuel spill zone, if active microbial populations are present, soil-gas oxygen concentrations are usually low (<5%) and soil-gas carbon dioxide (a metabolite of hydrocarbon degradation) may be high (>5%). Typically, soil gas concentrations in an uncontaminated area will be significantly different, with concentrations of oxygen (20.8%) and carbon dioxide (<0.5%) approximately equal to ambient concentrations (20.8%), and little to no TPH detected.

Low soil-gas oxygen concentrations are a preliminary indication that bioventing may be feasible at a site and it is appropriate to proceed to *in situ* respiration testing. For full-scale applications, it is useful to determine the entire areal extent and depth of soils with an oxygen deficit. If soil-gas oxygen concentrations are high (>5 to 10%), yet contamination is present, the soils may be sufficiently porous to allow natural aeration, and mechanical venting may not be needed. This situation is common to sites with a very shallow water table. Other factors may be limiting biodegradation (i.e. low moisture levels; contaminants toxic to microorganisms such as TCE and phenolics). The existence of significant contamination should be verified in the case of high soil-gas oxygen concentrations.

Soil Characterization

Determining the concentration and distribution of contaminants is a primary goal of soil characterization. The soil gas survey results can be utilized to focus the soil sampling program. A relatively large number of soil and soil gas samples must be collected to statistically delineate the vertical and lateral extent of contamination due to large variations in the distribution of contaminants at a site. Thus, soil gas sampling in concert with limited soil sampling is often sufficient to delineate the extent of contamination. The secondary goal of soil characterization is to collect data on the physical and chemical characteristics and the available nutrients within the vadose zone. Table 6-1 is a summary of the analytical protocol for soil samples.

Table 6-1. Soil Analytical Protocol for a Bioventing Site

Analyte	Analytical Method
Aromatic hydrocarbons (BTEX)	SW8020 (Purge and trap GC)
Total hydrocarbons, volatile and extractable (TPH)	SW8015 Modified (GC) - California LUFT Method
Moisture content	ASTM D-2216
pH	EPA 9045
Alkalinity	SM 403(M)
Total iron	EPA 6010
Total phosphorous	EPA 365.3
Total Kjeldahl nitrogen (TKN)	EPA 351.4
Grain size distribution	ASTM D422-63

Measurements of BTEX and TPH are necessary for delineation of the contamination. In addition, BTEX and TPH typically are of regulatory concern, therefore, these concentrations must be established. The moisture content is used with other physical parameters to estimate air-filled porosity. Parameters such as pH, alkalinity, and total iron content may affect the observed *in situ* respiration rates, because they are important characteristics known to impact microbial activity. Alkalinity and pH affect soil gas carbon dioxide concentrations such that, in high alkalinity soils, carbon dioxide production appears to be low due to the formation of carbonates. Conversely in low alkalinity soils, carbon dioxide production correlates well with oxygen consumption. Total iron may affect soil gas oxygen concentrations in that oxygen may react with iron in the soil. Iron is a nutrient required for microbial growth, but iron also may react with oxygen to form iron oxides, which can affect calculation of biodegradation rates. Total phosphorous and total Kjeldahl nitrogen are nutrients required for microbial growth and respiration. Low levels of these nutrients may affect microbial respiration. Particle size is an important indicator of permeability, which is important in assessing the potential for venting to oxygenate the zone of contamination.

In Situ Respiration (ISR) Testing

The ISR test provides a 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. The test provides a field measurement tool to simply assess whether the microorganisms are metabolizing the fuel by observing oxygen utilization. ISR testing is also conducted periodically to monitor the progress of site remediation, and the results are evaluated to decide when soil sampling to confirm cleanup, not to monitor progress, can be recommended (see Section 9). ISR tests have been used at numerous sites throughout the US and have been used at each of the Bioventing Initiative project sites. Details of ISR testing are discussed in Section 7.

Soil Gas Permeability Testing

On-site testing provides the most accurate estimate of the soil-gas permeability. On-site testing can also be used to determine the radius of influence that can be achieved for a given well configuration and flow rate. These data are used to design full-scale systems, specifically to space venting wells, to size blower equipment, calculate desired air flow rates, and to ensure that the entire site receives a supply of oxygen-rich air to sustain *in situ* biodegradation. Details of soil gas permeability testing are discussed in Section 7.

Radius of Influence

Traditionally, the radius of influence (R_I) is the maximum distance from the air extraction or injection well where vacuum or pressure (soil gas movement) occurs. With bioventing systems, R_I is more accurately defined as the maximum distance from the vent well where oxygenation occurs. It is a function of the soil properties, the configuration of the venting well, extraction or injection flow rates, and stratigraphy. If either the soil gas permeability or the radius of influence is high (> 0.01 darcy or a R_I > the screened interval of the vent well), this is a good indicator that bioventing may be feasible at the site and it is appropriate to proceed to soil sampling and full-scale design. If either the soil gas permeability or the radius of influence is low (< 0.01 darcy or a R_I < the screened interval of the vent well), this may indicate that bioventing may not be feasible, and the cost effectiveness of bioventing over other alternative technologies must be evaluated. Determination of R_I is discussed in Section 7.

Criteria for Removal Action

The NCP allows the Air Force to take any appropriate removal action if it determines there is a threat to public health or welfare or to the environment [40 CFR, 300.415 (b)(2)]. In making such a determination, the NCP specifies the consideration of eight criteria, but only two of these criteria are applicable at Air Force installations where bioventing can be potentially implemented:

- Actual or potential exposure to nearby populations, animals, or the food chain from hazardous substances, pollutants, or contaminants
- Actual or potential contamination of drinking water supplies or sensitive ecosystems

Based on the above general criteria, the following guidelines have been established for selecting specific sites at which removal of contaminants from vadose zone soils would be advisable.

Guidelines for Selecting Candidate Removal Sites:

- *Source of existing groundwater contamination*
- *High threat for potential groundwater contamination*
- *Migration of soil-gas plume*
- *High risk indicated from risk screening assessment*

Groundwater characterized by high concentrations of fuel hydrocarbons may be expected to be overlain by vadose zone soils having high soil gas concentrations of these contaminants. In some instances, the movement of fuel hydrocarbons may be from the groundwater into the vadose zone soils, and in others, from a source in the vadose zone into the groundwater. In either instance, removal of the vadose zone fuel hydrocarbons would reduce the threat of exposure to these contaminants.

Detection of high fuel hydrocarbon concentrations in soil gas indicate soils in the vadose zone that can serve as a continuing source of contamination to groundwater. Remediation of groundwater contamination cannot be efficiently achieved without addressing the source problems in the vadose zone. Therefore, sites at which there is a high degree of contamination in groundwater or vadose zone soils are appropriate candidates for removal action.

Indications of a moving soil-gas plume is another reason to consider a site to be a candidate for removal action. Workers and residents may be exposed to vapors migrating from the soil-gas plume, and soil-gas vapors might infiltrate buildings and crawl spaces, increasing the potential of exposure by inhalation and an explosion.

Risk screening can also provide candidates for a removal action. Even a qualitative site screening could indicate a high risk associated with soil contamination, indicating that a removal action should be considered. Factors which may be considered include the level of contamination, the presence of acutely toxic substances, public concern, the location of receptors, and the connection to groundwater. The quantitative results of a screening risk assessment can also be used to indicate whether or not a site should be considered a candidate for a removal action.

Section 7
BIOVENTING SYSTEM DESIGN AND COSTS

Introduction

This section describes bioventing system design and costs and is intended for use by project managers, engineers, and consultants actively involved in designing, constructing, and operating bioventing systems. The design of a bioventing system is based upon the results of site characterization and initial pilot testing activities, described in Section 6. This section provides additional details on system design, well design and construction, calculations and procedures used for *in situ* respiration testing and soil gas permeability testing, air flow management, and blower sizing. Typical unit costs and total system costs for a baseline bioventing system are also discussed in this section.

Bioventing System Configuration

A typical bioventing system schematic is shown on Figure 7-1. Air is either injected into or extracted from a collection of vent wells (VWs), screened across the area of contamination, in order to increase oxygen levels in the vadose zone. An electrically powered blower provides the necessary air flow, and a manifold system allows control of air flows for each individual well. Instrumentation consists of gauges to measure pressure, vacuum, temperature, and flow rate. For extraction systems, multiple sampling ports are provided for collecting vapor samples at key process locations within the system.

For air extraction systems, condensate and moisture must be removed with the use of a liquid separator. Off-gas treatment can be provided from a number remediation technologies, as described in Section 8. Air injection systems, which are preferred, do not require these additional components and are, therefore, much less expensive. Systems which combine air injection and extraction are also possible. These combination systems can be designed to prevent vapor migration into subsurface structures (e.g., basements), avoid creation of stagnant air zones, and eliminate the need for off-gas treatment.

In addition to the VWs used for active air injection or extraction, vapor monitoring points (MPs) are used to monitor system performance and are an important part of bioventing system design. A plan view of typical well placement is shown on Figure 7-2. The MPs are spaced radially around the VWs at distances expected to be under the influence of the VWs. One MP should be installed in an uncontaminated location where the soil type is similar to that at the site. This background MP serves as a control point for *in situ* respiration testing and provides important data on native soil gas conditions, soil total organic carbon content, and nutrient levels.

Well Design and Construction

Vent Wells (VWs)

Vent well construction is identical to that which would be used for a soil vapor extraction system and similar to that used for groundwater monitoring wells (except that the screened interval is located, at least partially, in the vadose zone). A typical VW construction diagram is shown on Figure 7-3. If existing groundwater monitoring wells are screened partially above the water table, they can also be used as air injection VWs; however, they should not be used for air extraction because the applied vacuum will cause a rise in the water table which could submerge the screened interval.

FIGURE 7-1
BIOVENTING SYSTEM SCHEMATIC

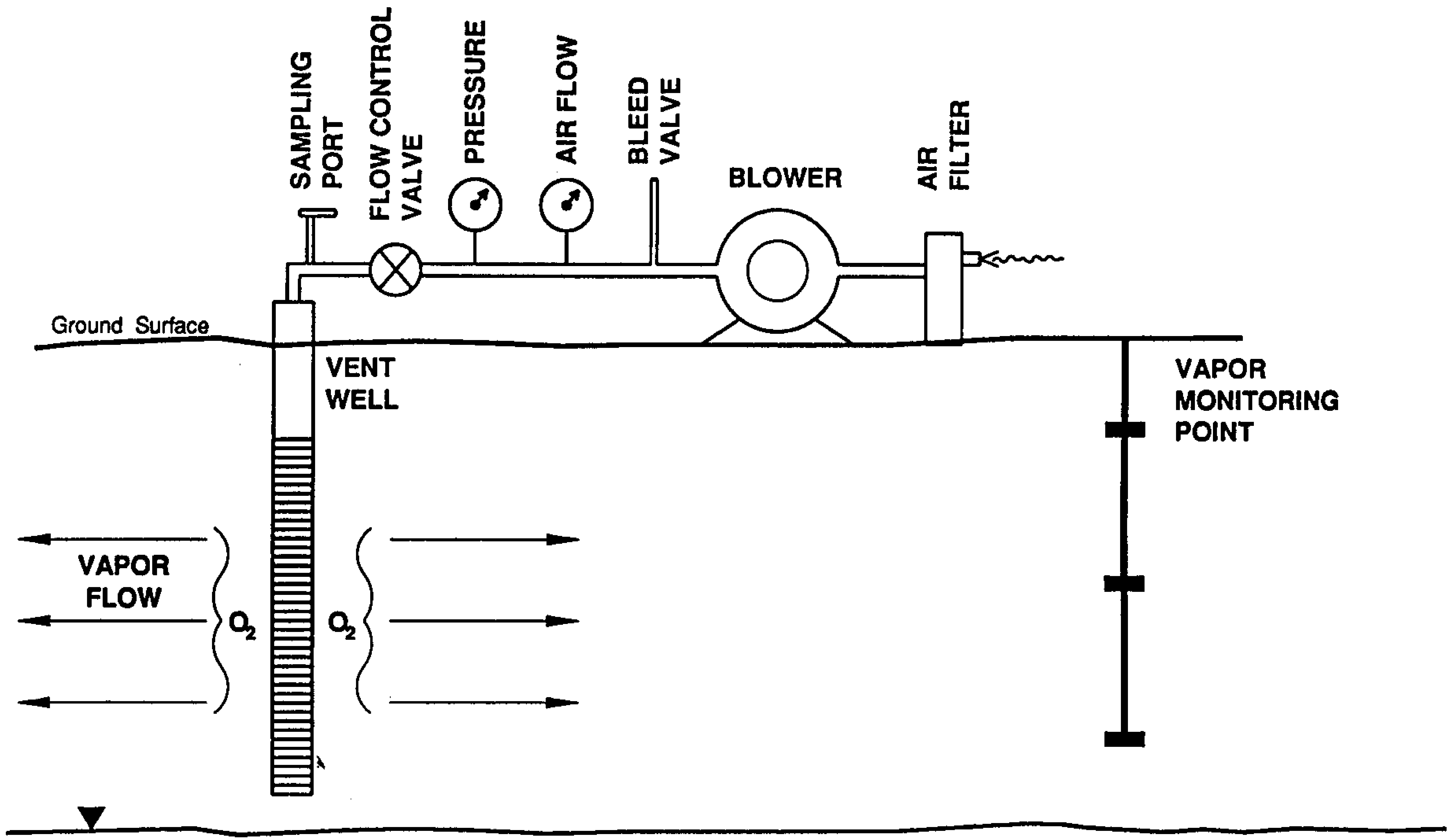

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FIGURE 7-2

PLAN VIEW OF BIOVENTING WELL PLACEMENT

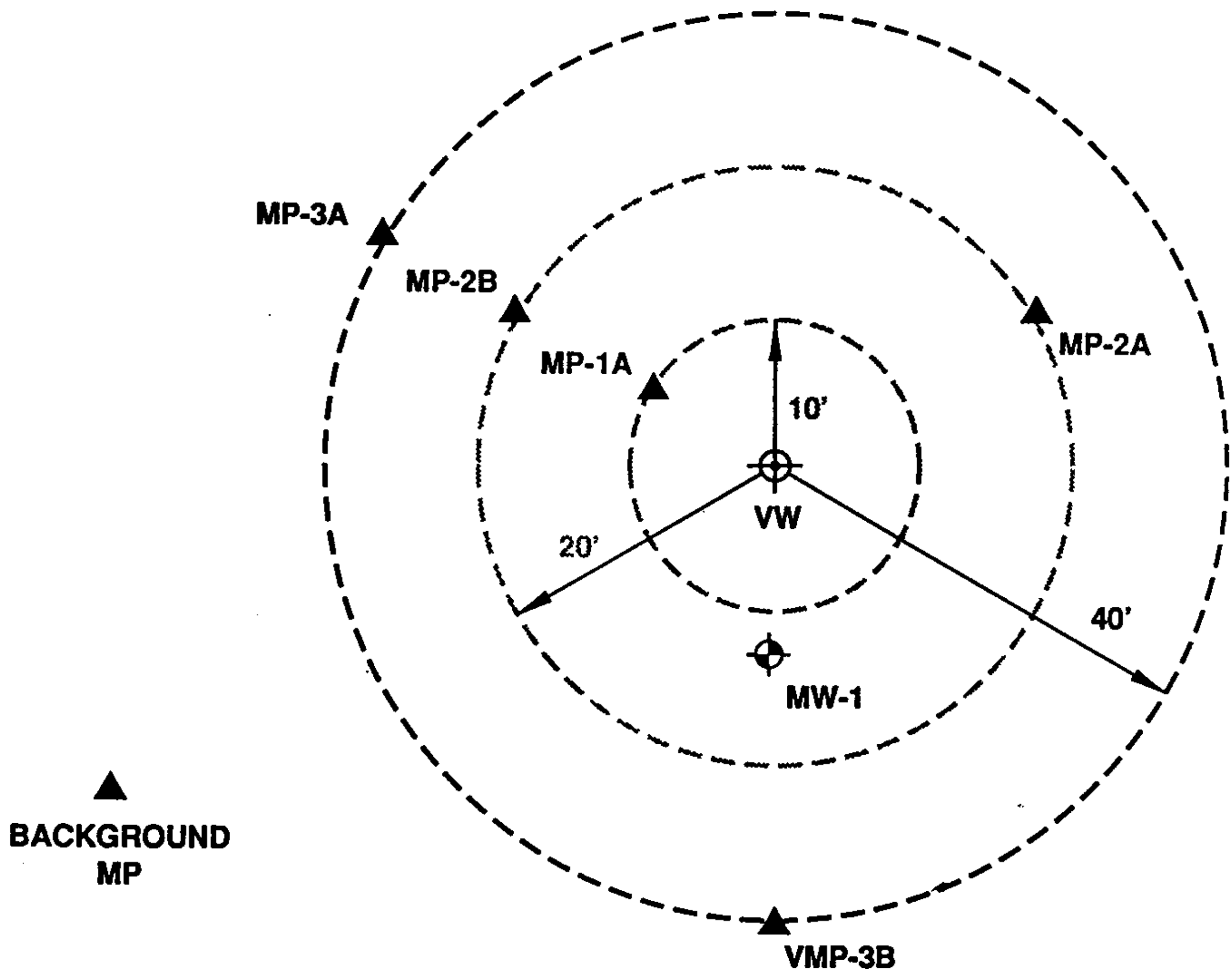

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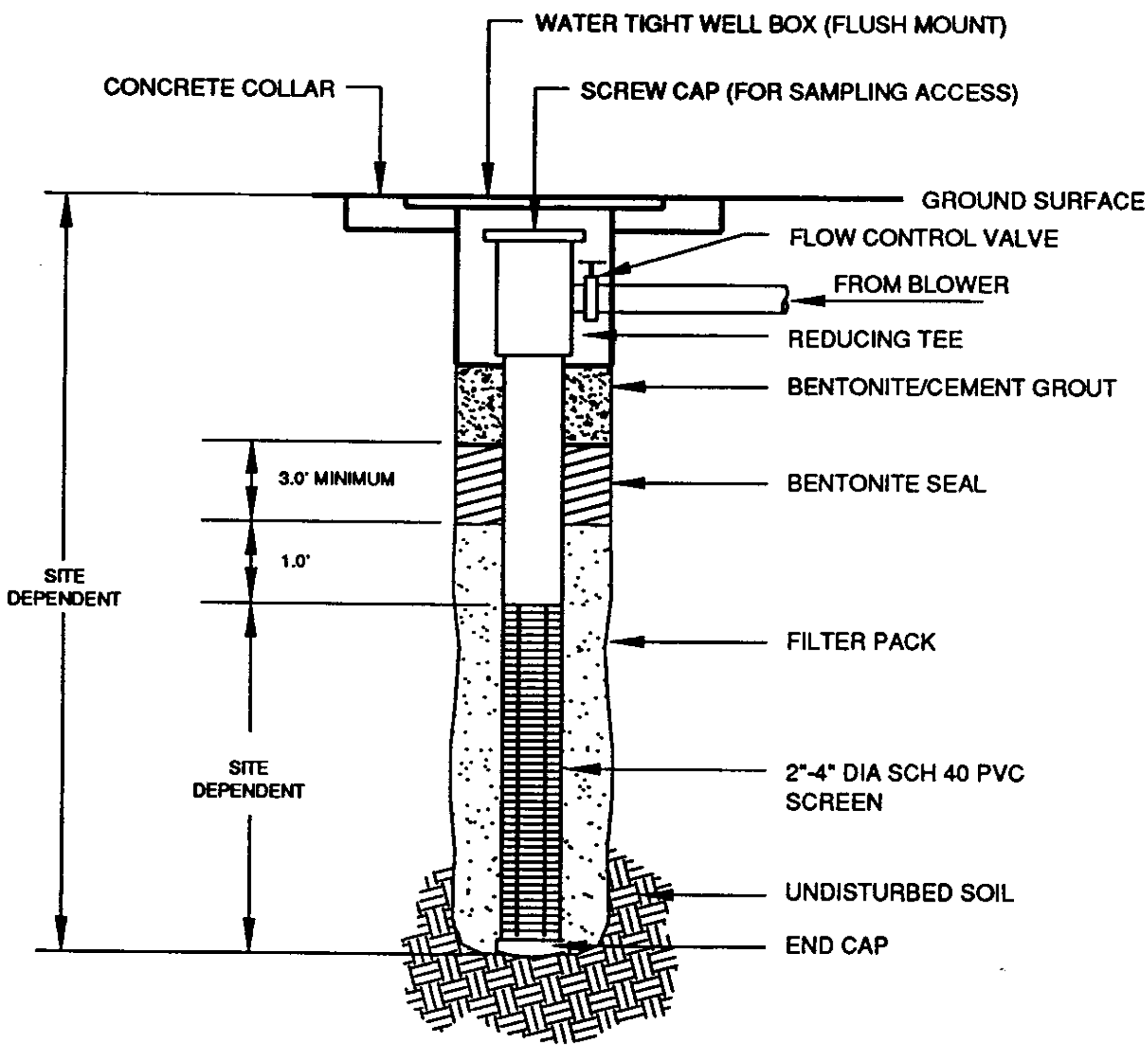
FIGURE 7-3

VENTING WELL CONSTRUCTION DIAGRAM (TYPICAL)



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The diameter of a VW is typically 2 or 4 inches, although smaller and larger diameters can be used. A 4-inch diameter or larger VW is recommended for sites with screened intervals longer than 30 feet in order to provide greater air flow for the larger soil volume. The screened interval of the VW should extend throughout the contaminated interval. For air injection systems, the screened interval should extend to the lowest historical water level (if contamination extends to the water table) in order to provide oxygen to the exposed capillary fringe.

Vapor Monitoring Points (MPs)

Vapor monitoring points are an essential part of any bioventing system design. They are used for measuring the oxygen, carbon dioxide, and contaminant concentrations in the soil gas; vacuum and/or pressure response from the VWs; and, soil temperature. A typical MP construction diagram is shown on Figure 7-4. Discrete screened intervals are used for each MP in order to monitor system performance in different soil types which may be present. If existing groundwater monitoring wells are screened above the water table, they can also be used as MPs provided sufficient air flow through the capillary fringe can be achieved from the VWs.

The MPs typically consist of nested, 0.25-inch schedule 80 PVC casings with 1-inch diameter screens approximately 6 inches long at the monitored depth. Bentonite seals at least 2 feet in thickness are placed above and below the filter pack in order to isolate the screen. The filter pack should extend 1 to 2 feet and the screen should be centered within the pack. Longer or coarser-grained filter packs should be used with less permeable or very moist soils. Thermocouples (type J or K) for measuring soil temperature should also be installed.

The MPs are spaced radially at distances from the VWs so that the radius of influence of the VWs can be obtained. The distances used will vary depending on soil type and the depth to the top of the VW screen. Recommended spacings are shown in Table 7-1. MPs should also be installed between any air injection VWs and locations which may be at risk of vapor migration (e.g. building basements).

In Situ Respiration (ISR) Testing

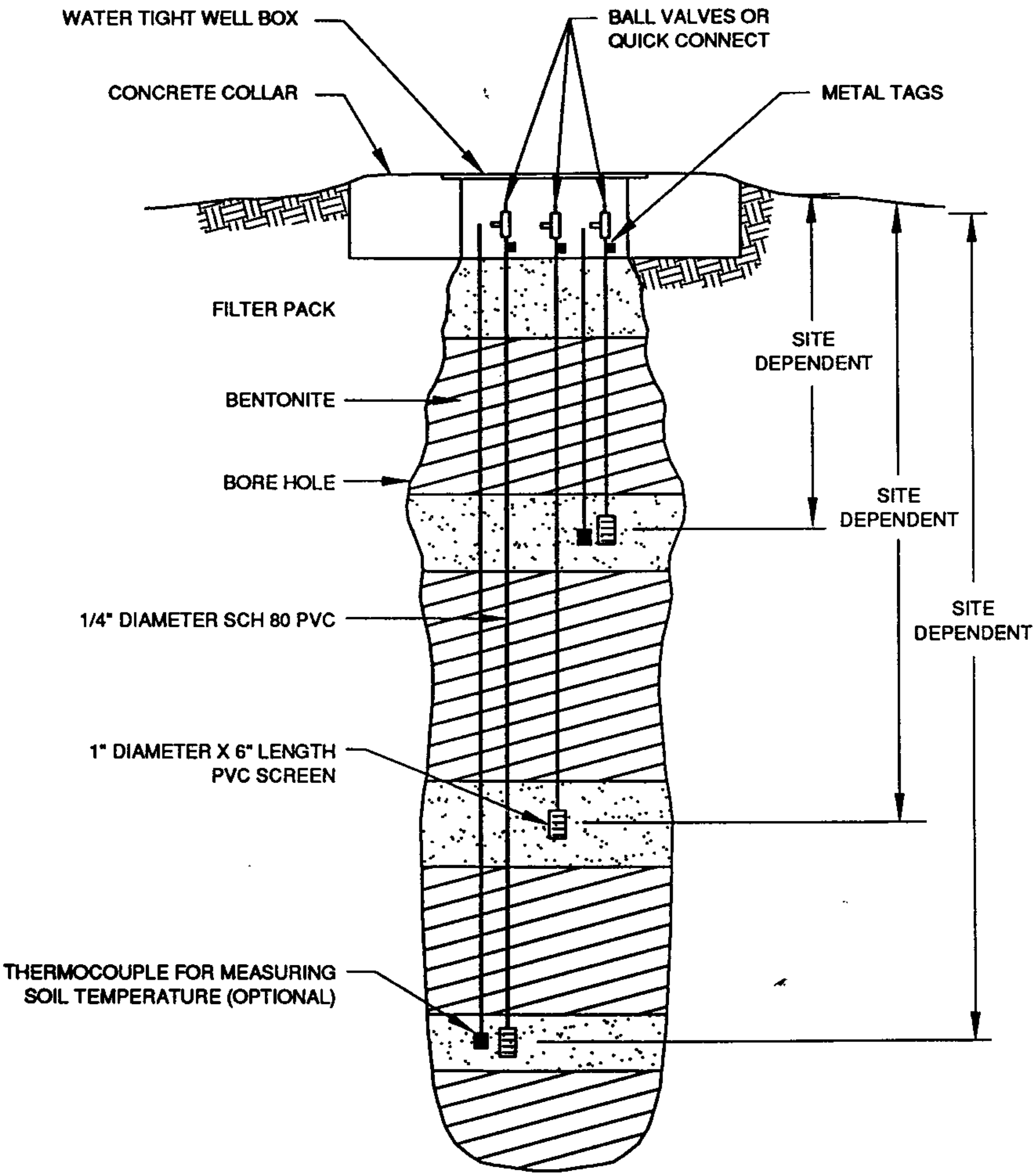
ISR testing is an important component of site characterization as discussed in Section 6. The test data are used for estimating rates of biodegradation. The test procedures described below are based on the method developed by Hinchee and Ong (1992) and are fully detailed in the *Test Plan and Technical Protocol for Bioventing* (Hinchee et al., 1992).

Testing Procedures

A mixture of air and an inert tracer gas (typically helium at 2% to 4% concentration) is injected into selected MPs for a period of approximately 20 hours with small, portable air pumps (approximately 1 scfm flow rate) in order to fully oxygenate the surrounding, oxygen-deficient soils in the contamination zone. The selected MPs are those where bacterial degradation is indicated by initially depleted oxygen levels and elevated carbon dioxide levels in soil gas. Locations are usually chosen where soil samples and soil-gas samples are also taken so that comparative data are generated.

FIGURE 7-4

VAPOR MONITORING POINT CONSTRUCTION DIAGRAM



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Following the period of injection, the pumps are shut off and oxygen and carbon dioxide levels in soil gas are monitored using field instruments for approximately 48 to 72 hours (or until oxygen is at or below 5%). Observed decreases in oxygen are largely attributable to usage by indigenous microorganisms for respiration during degradation of the fuel residuals. Typically, a rapid linear decrease in oxygen is observed, followed by a lag period after the oxygen concentration reaches about 5%. Oxygen-utilization rates are determined from the ISR test data by a zero-order relationship between oxygen versus time using only the linear portion of the curve. A typical response is shown on Figure 7-5.

Table 7-1. Recommended Spacing for Monitoring Points

Soil Type	Depth to Top of Vent Well Screen (feet) [1]	Monitoring Point Spacing Intervals (feet) [2]
Coarse Sand	5	5-10-20
	10	10-30-50
	>15	20-30-70
Medium Sand	5	10-20-30
	10	15-25-45
	>15	20-40-70
Fine Sand	5	10-20-40
	10	15-30-50
	>15	20-40-60
Silts	5	10-20-40
	10	15-30-50
	>15	20-40-60
Clays	5	10-20-30
	10	10-20-40
	>15	10-25-50

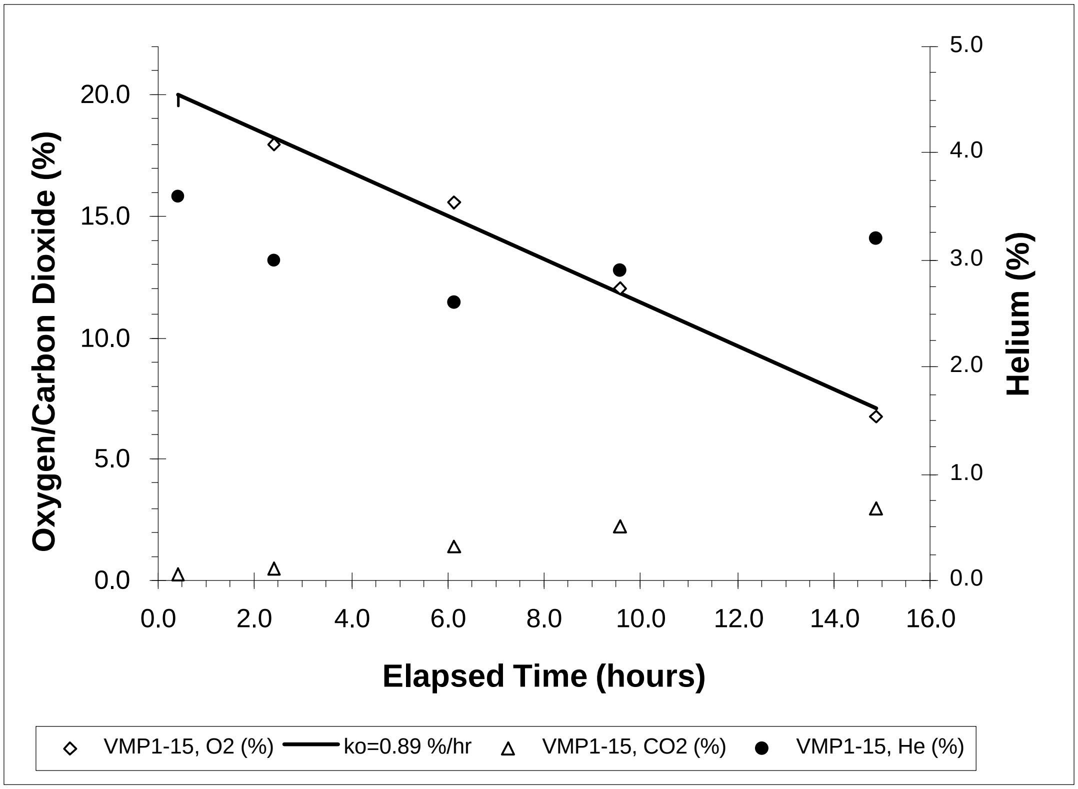
[1] Assumes 10 feet of vent well screen. For more than 10 feet of vent well screen, use >15-ft spacing.

[2] Monitoring point intervals based on venting flow rate of 1 scfm per foot of screen interval for clays and 3 scfm per foot of screened interval for sands.

Quality control checks in the field are performed to verify that measured decreases in oxygen are due to microbial utilization and not due to other mechanisms. The helium data collected at a site provide insight into whether observed oxygen-utilization rates are due to microbial utilization or to other effects such as leakage or diffusion. The molecular weight of helium is one-eighth that of oxygen and helium diffuses about 2.8 times faster than oxygen. Therefore, helium is more prone to diffusion and escape due to faulty well construction. Use of a tracer gas is particularly important for low permeability soils to verify that sufficient aeration of the soil volume has been achieved and that oxygen-depletion in soil-gas samples taken during the test are not due to the influx of oxygen-depleted soil gas from outside the zone of aeration.

An ISR test is also performed within clean soils to observe any oxygen uptake by soils due to sources other than microorganisms (i.e. humic materials, ferrous iron, etc.). Any oxygen uptake in clean soils is used to adjust oxygen-utilization rates observed in the contamination zone to properly estimate biodegradation rates.

Figure 7-5. *In Situ* Respiration Test Data



Calculation of Biodegradation Rates

The following stoichiometric relationship is usually employed to represent the oxidation of fuel-hydrocarbons to carbon dioxide and water:

$$C_6H_{14} + 9\tfrac{1}{2}O_2 \longrightarrow 6CO_2 + 7H_2O \qquad (7\text{-}1)$$

Based on this relationship, approximately 3.5 mg of oxygen are required to mineralize 1 mg of hydrocarbons. Using the above relationship and the oxygen-utilization rates measured during the ISR test, the biodegradation rate is calculated using the following equation:

$$k_B = \frac{-\frac{k_o}{100}\ \theta_a\ \rho_{O_2}\ R}{\rho_b}\ 8760 \qquad (7\text{-}2)$$

where:

k_B	=	biodegradation rate (mg hydrocarbons/kg soil per year)
k_o	=	oxygen-utilization rate (%/hr)
θ_a	=	air-filled porosity (cm^3 air/cm^3 soil)
ρ_b	=	soil bulk density or dry unit weight (g/cm^3)
ρ_{O_2}	=	density of oxygen (mg/L) [1,330 mg/L at 1 atm and 20 °C]
R	=	mass ratio of hydrocarbons to oxygen required for mineralization [1/3.5]
8760	=	number of hours per year

As previously mentioned, the oxygen-utilization rate, k_o, must be corrected for mechanisms other than microbial activity by subtracting any oxygen-utilization at the background MP. In addition, if the soil temperature at a site fluctuates significantly, it may be desirable to correct oxygen-utilization rates for temperature (Leeson and Hinchee, 1995).

The air-filled porosity and soil bulk density are difficult to accurately measure directly, but can be estimated from the total soil porosity and moisture content:

$$\begin{aligned} \theta_a &= n - \left[G\ w\,(1 - n)\right] \\ \rho_b &= G\,(1 - n) \end{aligned} \qquad (7\text{-}3)$$

where θ_a, ρ_b are defined in Eq. 7-2, and:

n	=	total soil porosity (cm^3 voids/cm^3 soil)
w	=	soil moisture content by weight (g moisture/g soil)
G	=	specific gravity of soil solids (g/cm^3) [usually estimated at 2.65]

The total soil porosity, n, is dependent on the soil type. Table 7-2 contains useful literature values. The soil moisture content, w, is usually measured by a soils laboratory using ASTM D2216. It should be noted that air-filled porosity is very sensitive to changes in total soil porosity (which is not directly measured) and moisture content.

Table 7-2. Soil Porosity of Various Soil Types

Soil Description	Porosity	Dry Bulk Density (g/cm3)	Reference
Sand, loose uniform	0.46	1.43	Terzaghi & Peck, 1967
Sand, fine	0.43	1.51	Morris & Johnson, 1967
Sand, loose mixed-grained	0.40	1.59	Terzaghi & Peck, 1967
Sand, medium	0.39	1.62	Morris & Johnson, 1967
Sand, coarse	0.39	1.62	Morris & Johnson, 1967
Sand, dense uniform	0.34	1.75	Terzaghi & Peck, 1967
Sand, dense mixed-grained	0.30	1.86	Terzaghi & Peck, 1967
Silt	0.46	1.43	Morris & Johnson, 1967
Clay, soft bentonite	0.84	0.43	Terzaghi & Peck, 1967
Clay, soft very organic	0.75	0.68	Terzaghi & Peck, 1967
Clay, soft slightly organic	0.66	0.93	Terzaghi & Peck, 1967
Clay, soft glacial	0.55	1.22	Terzaghi & Peck, 1967
Clay	0.42	1.54	Morris & Johnson, 1967
Clay, stiff glacial	0.37	1.70	Terzaghi & Peck, 1967
Glacial till, very mixed-grained	0.20	2.12	Terzaghi & Peck, 1967

Soil Gas Permeability Testing

As discussed in Section 2, soil gas permeability, k, is probably the most important site characteristic for a successful bioventing application. Several field and parameter estimation methods have been developed for determining soil gas permeability (Sellers and Fan, 1991). The most favored field method is the modified field-drawdown method, which is well-documented and will not be discussed in detail here (Johnson et al., 1990). The Hyperventilate™ computer program has been produced for storing field data and to ease computations (USEPA, 1993c).

Testing Procedures

The general approach involves the injection or extraction of air at a constant flow rate into a single VW while measuring the pressure/vacuum changes at MPs which are spaced at various distances from the VW. If the soil vacuum or pressure response is relatively slow (on the order of hours), a dynamic solution is used to estimate k. If the soil vacuum or pressure response is relatively fast (on the order of minutes), a steady-state solution is used to estimate k. When the data allows, both methods are used in order to compare calculated soil gas permeability values.

One of the main objectives of a soil gas permeability test conducted for full-scale bioventing design is to determine the extent of the subsurface which can be oxygenated from a single VW. In addition to vacuum or pressure response, oxygen response over time is also measured at each MP to determine the region influenced by the VW.

Theoretically, the determination of soil gas permeability using this method is independent of the flow rate used. However, because oxygen response in the MPs is used to help quantify the radius of oxygen influence of the VW, a flow rate should be chosen which closely approximates that which will be used during normal system operations. A method for estimating this target flow rate is described later in this section.

Calculation of Soil Gas Permeability (Dynamic Response)

Using the modified field-drawdown method, the equation for vacuum/pressure response for MPs under the influence of one VW predicts that, in the dynamic range, response versus ln(time) is a straight line. A typical response for an air injection test is shown on Figure 7-6. The slope of the best-fit straight line through points in the dynamic range can be related to soil gas permeability by the following equation:

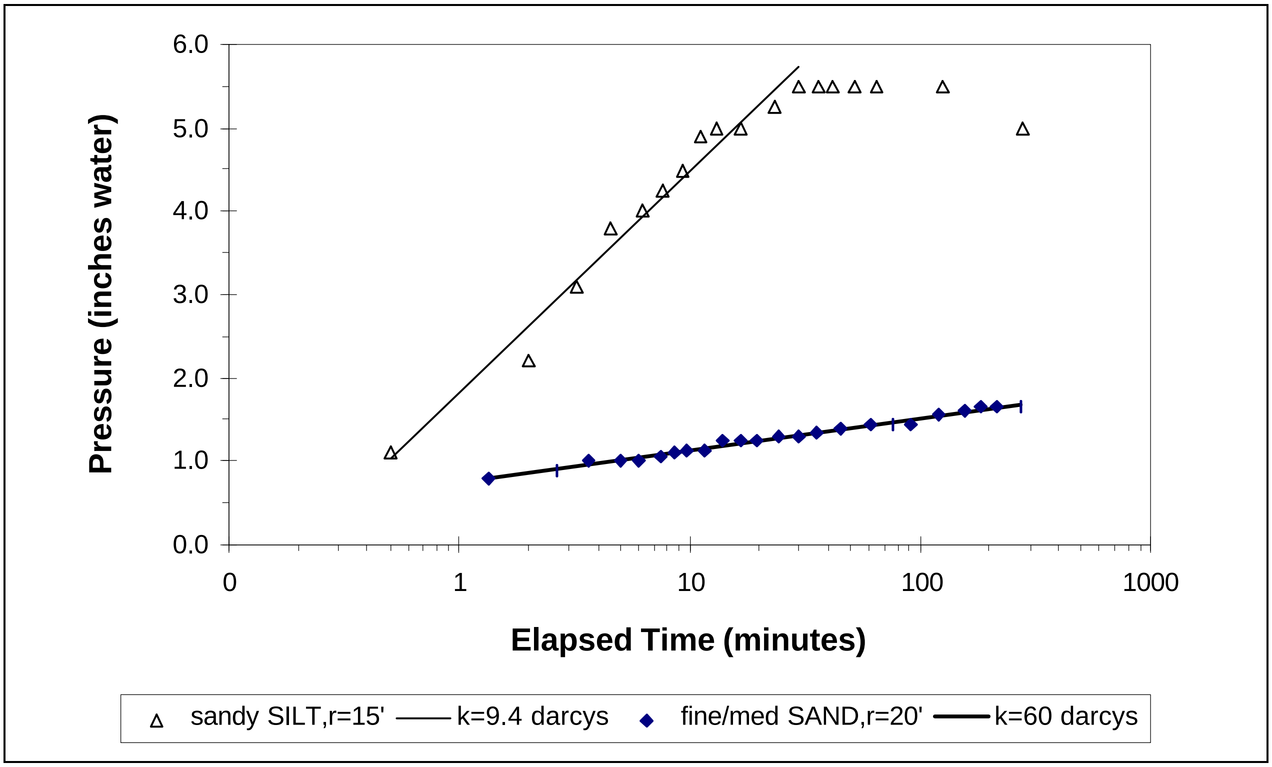
$$k = \frac{Q\,\mu}{4\,A\,\pi\,H} \qquad (7\text{-}4)$$

where:

	k	=	soil gas permeability (cm^2)
	Q	=	volumetric air flow rate through the stratum (cm^3/s)
	A	=	slope of the vacuum/pressure response (P’) vs. ln(t)
	P'	=	“gauge” pressure at the MP ($g/cm\text{-}s^2$) ($P' < 0$ for air extraction)
	t	=	elapsed time since start of test (s)
	H	=	stratum thickness in which air flow occurs (cm)
	μ	=	viscosity of air (g/cm-s) [1.8×10^{-4} g/cm-s at 18 °C]

Typically the length of the VW screened interval is used for the stratum thickness, H, and the total flow rate through the VW is used for the flow rate, Q. However at sites where the VW is screened across zones of varying permeabilities, the analysis is more complex because an estimate must be made for how much air flow, Q, occurs in each zone.

Figure 7-6. Dynamic Response During Permeability Test



Calculation of Soil Gas Permeability (Steady-State Response)

Using the modified field-drawdown method, the equation for vacuum/pressure response for MPs under the influence of one VW predicts that, at steady-state, soil gas permeability is given by the following equation:

$$k = \frac{Q\,\mu\,\ell n\left(\frac{R_w}{R_I}\right)}{H\,\pi\,P_{atm}\left[1 - \left(\frac{P_w}{P_{atm}}\right)^2\right]} \qquad k = \frac{Q\,\mu\,\ell n\left(\frac{R_w}{R_I}\right)}{H\,\pi\,P_w\left[1 - \left(\frac{P_{atm}}{P_w}\right)^2\right]} \qquad (7\text{-}5)$$

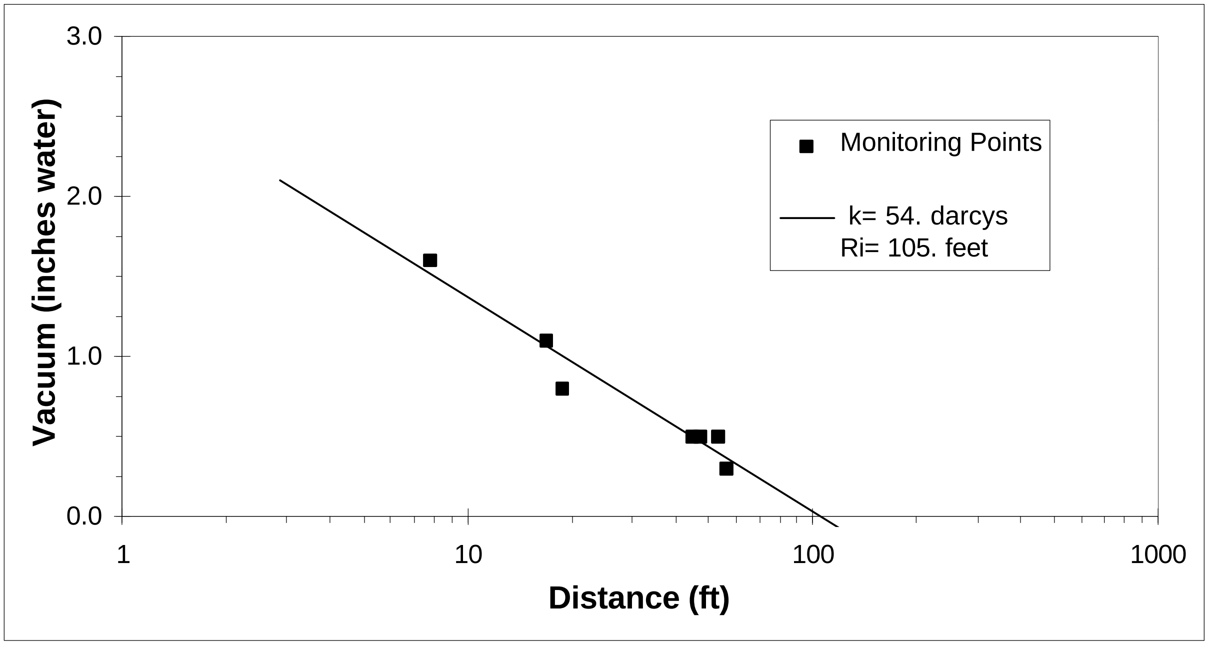
injection systems — extraction systems

where k, Q, *m*, and H were defined in Eq. 7-4, and:

R_w	=	radius of the VW (cm)
R_I	=	maximum radius of vacuum/pressure response at steady-state (cm)
P_w	=	absolute pressure at the VW (g/cm-s)
P_{atm}	=	absolute ambient atmospheric pressure (g/cm-s) [1.01 x 10^6 at sea level]

Note that a different equation must be used, depending on whether air is extracted from or injected into the VW. A typical response from an air extraction test is shown on Figure 7-7.

Figure 7-7. Steady-State Calculation Method



Determining the Radius of Influence

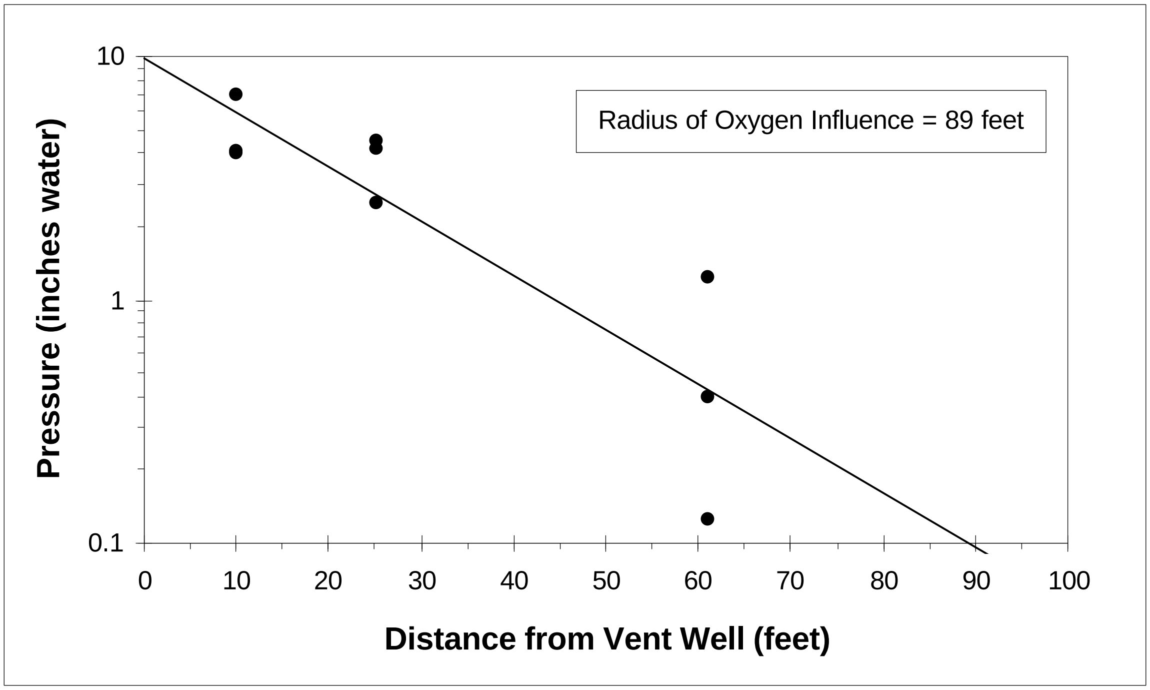
The radius of vacuum/pressure response, R_I, as defined in Eq. 7-5, is usually determined by plotting the vacuum/pressure response of the MP versus the log of its radial distance from the VW and extrapolation of the best-fit line to zero vacuum/pressure, as shown on Figure 7-7. For the purposes of calculating soil gas permeability, this definition for R_I should be used.

However, from a design point of view, the radius of influence is better defined as the distance from the VW where some level of remediation is occurring. For bioventing systems, it is the radial distance at which oxygen levels increase that determines remediation. This radius of oxygen influence may not be equivalent to the radius of vacuum/pressure response, R_I. Long-term increases in the effective radius of oxygen influence beyond measurable or inferred vacuum/pressure response could be expected due to diffusion of oxygen in the subsurface. If microbial activity is high, increased oxygen consumption may reduce the radius of oxygen influence. At sites with low permeability soils, vacuum or pressure gradients may not result in significant gas flow.

The radius of oxygen influence is best determined by measuring oxygen levels in the soil gas after equilibrium has been reached. However, it may take days or weeks for equilibrium to occur and previously installed MPs may not be spaced optimally to accurately determine the proper distance.

Based on data collected from the AFCEE Bioventing Initiative, an empirical method has been developed by for determining radius of oxygen influence for air injection systems (Leeson and Hinchee, 1995). The log of the pressure at each MP is plotted versus the distance of the MP from the VW. The radius of influence is then taken as the distance at which the best fit line intersects 0.1 inches of water pressure. This technique illustrated on Figure 7-8.

Figure 7-8. Radius of Oxygen Influence Determination (Injection Systems)



Air Flow Rate Management

For bioventing systems, remediation is dependent only on providing oxygen above the biological demand. Minimizing the flow rate minimizes hydrocarbon volatilization and emissions of volatile hydrocarbons to the atmosphere. Oxygen levels in soil gas of only 5% by volume are considered sufficient for aerobic biodegradation, which is not difficult to achieve with low flow rates. Soil-gas exchange rates of less than one pore volume per day are usually more than adequate.

The following equation can be used to estimate the required air flow rate:

$$Q = \frac{k_o \; V \; \theta_a}{(C_{max} - C_{min}) \; 60} \qquad (7\text{-}6)$$

where:
- Q = volumetric air flow rate (ft^3/min)
- k_o = oxygen-utilization rate (%/hr)
- θ_a = air-filled porosity (cm^3 air/cm^3 soil)
- V = volume of contaminated soil being aerated (ft^3)
- C_{max} = oxygen concentration of background/injected air (%) [typically 20.9%]
- C_{min} = minimum oxygen concentration for aerobic conditions [typically 5.0%]
- 60 = number of minutes in one hour

The oxygen-utilization rate, k_o, is measured during the *in situ* respiration test, which is described earlier in this section and shown on Figure 7-5. The air-filled porosity, θ_a, is also discussed earlier in this section and can be calculated from Equation 7-3. The volume of contaminated soil being aerated, V, is dependent on the thickness of the VW screened interval (usually equal to the thickness of the contaminated interval) and the radius of oxygen influence of the VW. When using Eq. 7-6 to estimate the flow rate to use for a soil gas permeability test (i.e. before the radius of oxygen influence is known), the maximum spacing interval for a MP given in Table 7-1 can be used for the approximate radius of oxygen influence.

When multiple wells are installed at a site, spacing between the VWs is conservatively estimated at 1.5 times the radius of oxygen influence; however, more complex analysis and vapor flow modeling may be desirable in order to try to optimize well spacing and minimize costs (Johnson and Ettinger, 1994; Mohr and Merz, 1995). The piping manifold should allow for flow rates to be measured and readjusted at individual wells through the use of separate gauges and isolation valves.

Consideration must also be given to air flow patterns, since stagnation areas may be produced with multiple injection or extraction wells. A combination of air extraction and air injection wells (possibly utilizing reinjection of extracted vapors) or alternating injection wells can reduce or eliminate these stagnation areas.

Blower Sizing

Selection of the proper blower for a bioventing system requires consideration of the necessary flow rate, the backpressure or vacuum from the VWs, the pressure drop in the system piping and, if installed, the pressure drop of the off-gas treatment system.

Two basic types of blowers are typically used: regenerative (centrifugal) and positive displacement. Positive displacement blowers are useful for sites with higher pressure or vacuum requirements (up to 10 psi), but are more expensive to maintain. Regenerative blowers can produce higher flow rates and are inexpensive to maintain, but have limited vacuum and pressure limits (on the order of 2-3 psi). Since most bioventing systems have relatively low vacuum or pressure requirements, regenerative blowers are more commonly used.

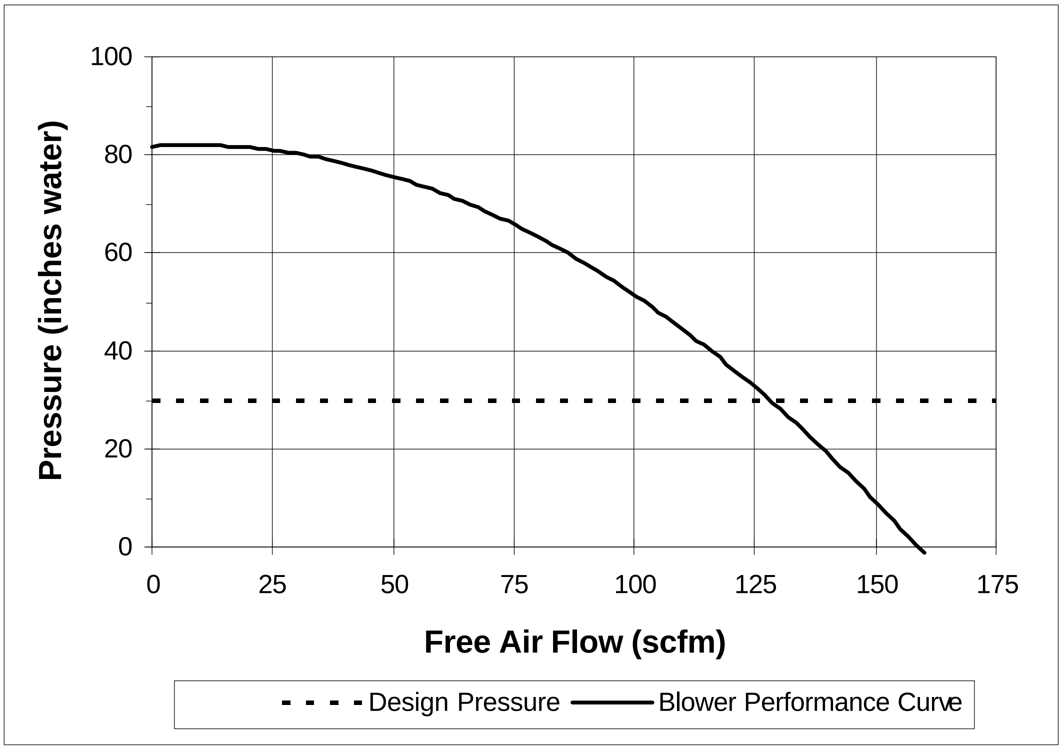
Choosing the wrong blower can result in insufficient oxygen delivery to the contaminated soils, lengthen remediation time, shorten blower life, and increase costs. A blower should be chosen which operates under field conditions near the middle of its operating range to minimize capital costs while not overstressing the blower.

The two most important parameters for sizing blower systems are: 1) the expected total pressure or total vacuum at the VWs, and; 2) the total air flow rate required. Unless extensive manifold piping is used, the pressure drop of system piping is usually negligible. Consideration must also be given to possible temporal changes at the site. For example, soil gas permeability, radius of influence, and air flow rate are all increased by a falling water table. Therefore, a slight overdesign of the system and an air flow bypass system is usually employed (see Figure 7-1). Flow rates can then be adjusted as site conditions require.

The expected vacuum or pressure at VWs is measured during soil gas permeability testing (see Eq. 7-5). Using results from soil gas permeability tests and *in situ* respiration tests, the required air flow rate can be calculated from Eq.7-6. Blower curves provided by the blower manufacturer are then used in sizing the blower. Blowers for most small to medium-sized bioventing sites will require 230-volt, single phase power connections and will be rated to 2.5-horsepower or less.

A sample blower curve is shown on Figure 7-9 for a typical air injection regenerative blower. The design extraction vacuum or injection pressure is first determined, then the flow rate produced by the blower at that vacuum or pressure is read from the blower curve. The flow rate produced should be greater than the required flow rate and should be in the middle of the blower's operating range. Excess air flow produced by the blower is vented to or from the atmosphere through the bypass system. Individual flow rate adjustments at the VWs and for the bypass system are performed by adjusting the manifold piping valves and reading the air flow gauges.

Figure 7-9. Sample Blower Performance Curve



Quantification of Biodegradation and Volatilization Rates During Air Extraction

For air extraction bioventing systems, biodegradation and volatilization of hydrocarbons can be quantified through measurement of the oxygen, carbon dioxide, and hydrocarbon concentrations in the extracted soil gas. In addition, bioventing systems that are operating in injection mode can be reconfigured as an extraction system for a short time in order to provide a check on biodegradation rates. This is an important part of performance monitoring and process evaluation (Section 9).

The following equation can be used for quantifying the volatilization component:

$$\dot{m}_{vol} = \frac{(28.3)\,(1440)}{(454)\,(10^{6})}\, Q\, C_{tvh} \qquad (7\text{-}7)$$

where:

$\dot{m}_{vol}$	=	mass rate of hydrocarbons volatilized (lbs/day)
Q	=	air extraction flow rate (ft^3/min)
C_{tvh}	=	concentration of total volatile hydrocarbons in extracted soil gas (µg/L)
28.3	=	number of liters per ft^3
1440	=	number of minutes per day
454	=	number of grams per lb
10^6	=	number of micrograms per gram

The concentration of hydrocarbons in the extracted soil gas, C_{tvh}, is typically estimated from field instruments or measured using laboratory analysis.

The following equation can be used for quantifying the biodegradation component:

$$\dot{m}_{bio} = \frac{(28.3)\,(1440)}{(454)\,(10^{3})}\, Q\ R\ \rho_{O2}\ \frac{\left(C_{bkgd} - C_{O2}\right)}{100} \qquad (7\text{-}8)$$

where:

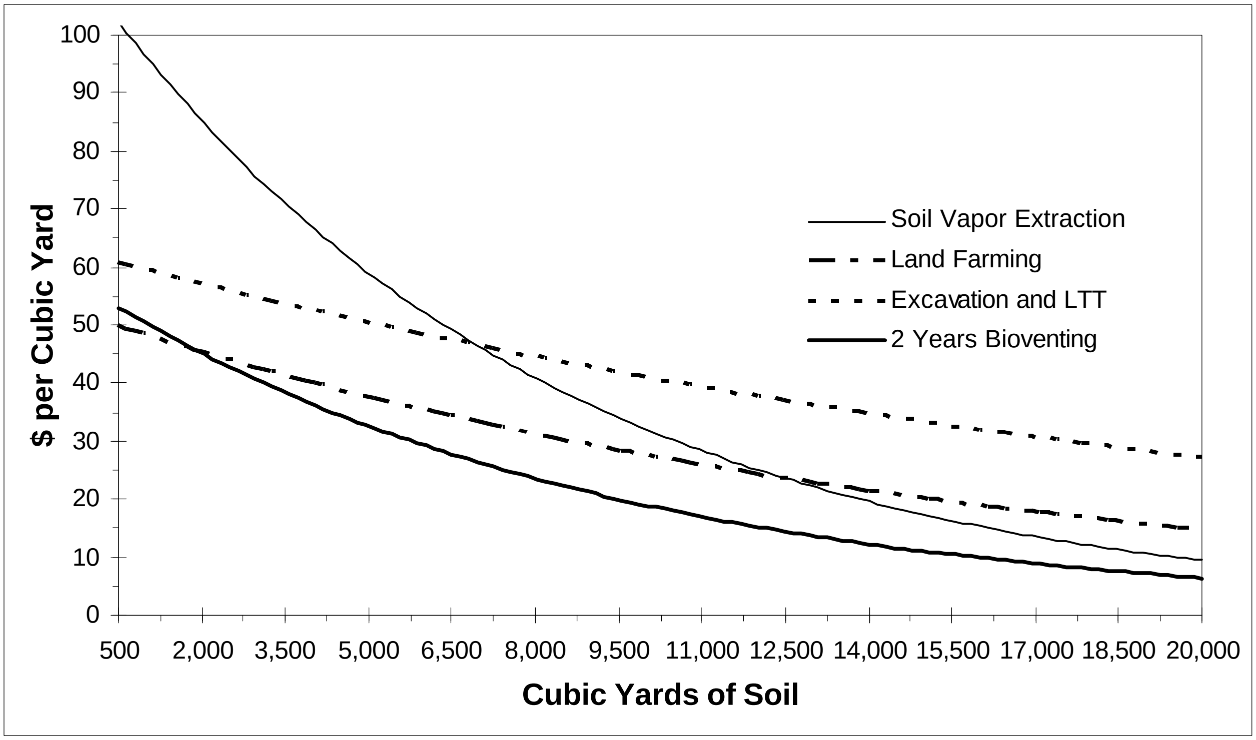
$\dot{m}_{bio}$	=	mass rate of hydrocarbons biodegraded (lbs/day)
Q	=	air extraction flow rate (ft^3/min)
C_{bkgd}	=	concentration of oxygen in background soil gas (%)
C_{O2}	=	concentration of oxygen in extracted soil gas (%)
R	=	mass ratio of hydrocarbons to oxygen required for mineralization [1/3.5]
ρ_{O_2}	=	density of oxygen (mg/L) [1,330 mg/L at 1 atm and 20 °C]
28.3	=	number of liters per ft^3
1440	=	number of minutes per day
454	=	number of grams per lb
10^3	=	number of milligrams per gram

Costs

Based on recent commercial application of the bioventing technology and data collected from the AFCEE Bioventing Initiative, the total unit cost of using bioventing for *in situ* soil remediation is $10 to $60 per cubic yard. At sites with more than 10,000 cubic yards of contaminated soil, costs of less than $10 per cubic yard have been achieved. Although costs can be higher with smaller sites, bioventing offers significant advantages over disruptive excavation operations or expensive off-gas treatment from soil vapor extraction operations. Figure 7-10 provides a comparison of unit costs for bioventing and other remediation technologies.

Table 7-3 lists costs for a baseline bioventing system, including the design basis used to estimate the costs. The cost information was obtained from vendors of equipment and from costs incurred at over 100 bioventing sites that are part of the AFCEE Bioventing Initiative. The design basis used is for an air injection bioventing system (no off-gas treatment required), with two VW and four vapor MPs. This system could be expected to treat approximately 5,000 yd^3 of soil contaminated with 3,000 mg/kg of petroleum hydrocarbons.

Figure 7-10. Comparison of Costs for Various Remedial Technologies for Fuel-Contaminated Soils



The costs listed in Table 7-3 should only be used as a guideline. Costs are not included for site characterization or site closure activities, since these costs would be incurred with any remediation alternative. Therefore, the costs in Table 7-3 should be used for comparison purposes only and not as absolute cleanup costs. A detailed, site-specific cost analysis will be required in many cases, especially those involving many VWs, off-gas treatment, low permeability soils, deep subsurface contamination (below 50 feet bgs), or significant regulatory involvement.

Table 7-3. Baseline Bioventing Cost Estimate

Item	Design Basis	Unit Cost[1]	Unit	Qty	Item Cost
Admin./Management	procurement, client/regulatory meetings, technical oversight	$ 70	hour	65	$ 4,550
Site Visit/Planning	one site visit, plus site historical data review	$ 70	hour	50	$ 3,500
Work Plan Preparation	prepared as addendum to master protocol/procedures document	$ 70	hour	120	$ 8,400
Regulatory Oversight	one comment/review process; familiar and receptive regulatory environment	$ 70	hour	40	$ 2,800
Site Preparation					
- Field Prep	permitting, supplies, equipment	$ 50	hour	40	$ 2,000
- Drilling	2 VWs, 4 MPs, 40 feet bgs	$ 75	foot	240	$ 18,000
	2 technicians for 5 days	$ 50	hour	80	$ 4,000
		$ 100	per diem	10	$ 1,000
	soil disposal	$ 200	drum	10	$ 2,000
- Electrical	230V, 30A, single-phase power available within 30 feet	$ 70	hours	16	$ 1,120
- Blower/piping/misc	1-HP regenerative rated to 60 scfm plus misc. supplies	$ 1,900	misc.	1	$ 1,900
Laboratory Sampling					
- soil	standard analysis suite; 2 per borehole	$ 450	sample	12	$ 5,400
- soil gas	standard analysis suite; 1 from each VW, 2 from each MP	$ 130	sample	10	$ 1,300
Initial Pilot Testing					
- permeability test	2 technicians for 1 day	$ 50	hour	16	$ 800
		$ 100	per diem	2	$ 200
- *in situ* respiration test	2 technicians for 4 days	$ 50	hour	64	$ 3,200
		$ 100	per diem	8	$ 800
- system startup	2 technicians for 2 days	$ 50	hour	32	$ 1,600
		$ 100	per diem	4	$ 400
- test equipment rental	field meters, sampling equipment	$ 200	day	5	$ 1,000
Pilot Test Results Report		$ 70	hour	150	$ 10,500
O&M					
- operations	check system 1 hour per week for 2 years	$ 0 (site owner)	hour	104	$0
	electrical costs for 2 years	$ 0.075	kWh	13000	$ 975
- system monitoring	2 follow-up ISR tests	$ 4,000	test	2	$ 8,000
- monitoring reporting	2 short reports of monitoring results	$ 70	hour	40	$ 2,800

Notes:
[1] Labor rates are average of all personnel used

Total: **$ 86,245**
Cost per cubic yard treated: **$ 17**

Section 8
ALTERNATIVE BIOVENTING SYSTEM CONFIGURATIONS

Alternative system configurations to the baseline bioventing approach may be required at some Air Force sites to improve performance. The term "alternative system configuration" is defined to mean any substantial modification of the baseline system at any site, beyond the simple design modifications described in Section 7. All alternative configurations to the baseline design are considered to be within the scope of the bioventing presumptive remedy, which refers to the general process of venting the subsurface with fresh air to promote *in situ* bioremediation. The following subsections summarize alternatives to conventional bioventing systems, additional design considerations, and additional monitoring options.

Alternatives to Conventional Bioventing Systems

Bioventing may be combined with other procedures to enhance the removal or biodegradation of contaminants. Some of these methods include the use of pure oxygen injection, addition of surfactants to increase contaminant mobility, soil warming techniques, or ozonation. Also, air sparging, a relatively new technology being examined for *in situ* remediation of contaminated groundwater, can be combined with a source removal mechanism such as bioventing.

Pure Oxygen Injection

A gas stream with a higher oxygen content than the atmosphere may be used for bioventing. This reduces the required gas injection rate, therefore, the use of pure oxygen injection can be advantageous at sites where unacceptable levels of volatilization may become a regulatory concern. Pure oxygen injection also may be considered in low-permeability soils where the ability to inject air is limited. The use of pure oxygen is much more expensive than traditional bioventing. The requirements to remediate 1 acre to a depth of 10 feet containing 4,000 mg of hydrocarbon per kg of soil would require approximately 6 to 7 million cubic feet of oxygen, which would result in a cost of approximately $80,000 for the oxygen alone (Leeson and Hinchee, 1995).

Surfactants

As discussed in Section 2, bioavailability of the contaminant is a critical parameter affecting the extent of *in situ* bioremediation. Compounds with greater aqueous solubilities and lower affinity to sorb onto the soil generally are more bioavailable to soil microorganisms and are more readily degraded. The use of surfactants can increase the solubility and therefore the availability of compounds. The use of surfactants *in situ* to enhance biodegradation has not been well documented, and few laboratory studies have been conducted. The disadvantages associated with the use of surfactants are the cost involved and the danger of spreading surfactants beyond the boundaries of the contaminated area. Most regulators are hesitant to grant approval to the testing of surfactants due to the possibility of greater contamination from the surfactants themselves. Thus, pending further controlled field applications, utilization of surfactants is not recommended.

Soil Warming

As discussed in Section 2, soil temperature greatly affects microbial processes. However, soil heating has a high energy demand that may not justify the incremental increase in biodegradation rates. A study conducted at Eielson AFB Alaska examined the effect of different forms of soil warming to increase soil temperature (Leeson et al., 1993). The effect of increased soil temperature on the biodegradation of JP-4 contaminants was studied. Biodegradation rates were studied in three test plots: an active warming test plot (appling heated water to the subsurface), a passive warming test plot (plastic sheeting placed at surface), and a surface warming test plot (heat tape placed in trenches 3 feet deep). Biodegradation rates in the active and surface warming test plots were consistently higher than those observed in the passive warming or control test plot.

In Situ Air Sparging (IAS)

This relatively new treatment technology involves injection of clean air directly into an aquifer to remove more volatile and less soluble contaminants by physical stripping. The volatiles are transported to the vadose zone, where they can be collected and removed via a soil vapor extraction system. Increased biological activity is stimulated in the capillary fringe area by increased oxygen availability (Leeson et al. (1993). Information on the distribution and flow configuration of the injected sparging air is essential to interpreting performance of IAS systems and evaluating their applicability. More information is needed to understand IAS systems, and IAS is not recommended without conclusive pilot test data or at sites with a highly heterogeneous geologic setting.

In-Well Aeration

This technology is primarily a groundwater remediation technology which involves injection of clean air at the bottom of a groundwater well in order to strip contaminants and circulate groundwater near the well. The air injection results in an in-well air lift pump effect and air stripping to remove volatiles. The air lift pumping effect also establishes a circulation pattern of oxygen-saturated water in the aquifer which may enhance the biodegradation rate. In-well aeration has the potential to be more cost-effective and efficient than conventional pump-and-treat technology but will be subject to similar limitations.

Ozonation

The injection of ozone into contaminated soil has generally been applied primarily as a means of partially oxidizing the more recalcitrant compounds to increase their biodegradability (Leeson and Hinchee, 1995). In one study of soils contaminated with PAHs, a significant reduction in total aromatic hydrocarbons was observed after ozonation, and carbon dioxide production was also seen to increase, indicating increase in microbial activity (Lund et al., 1991). Ozone injection has several advantages, including providing an alternative source of air to microorganisms. However, the cost of operating an ozonation system would be high, due to the cost of ozone production and more costly materials of construction (stainless steel equipment is required to resist ozone attack).

Additional Design Considerations

The topics discussed in the following subsections typically are not required at most sites and were not included in Section 7. However, in some cases, options such as free product removal or dewatering must be considered for site remediation.

Conventional Free Product Removal

Regulatory guidelines generally require that free-product recovery take precedence over other remediation technologies, and conventional removal actions complete free-product removal prior to initiating vadose zone remediation. This phased approach is costly and slow because free-product recovery technologies have little or no effect on soil contamination. Conventional dual-pump free-product recovery systems, involving a pump below the water table to induce drawndown and a second extraction pump to recover free product, are generally efficient in preventing migration of contaminants, but can require extraction of large volumes of groundwater that must be treated prior to discharge. Vacuum-enhanced pumping systems use the same concept as dual-pump systems, except that the cone of depression actually is a cone of reduced pressure around the well. Maximum attainable suction lift might appear to be a limitation to application of vacuum-enhanced dewatering. Conventional free-product recovery skimmer systems generally are inefficient because they have little effect on free product outside the recovery well, so efficiency relies on the passive movement of free product into the recovery well.

Bioslurping

This is a new technology application that combines vacuum-assisted free-product recovery with bioventing to simultaneously recover free-product and remediate the vadose zone. Unlike other free-product recovery technologies, bioslurping systems treat both saturated and unsaturated zones simultaneously. Bioslurping pumps are designed to extract free-phase fuel from the water table and to aerate vadose zone soils through soil gas vapor extraction. The systems can also be designed to achieve hydraulic control as is done with conventional pump-and-treat technology. The bioslurper system withdraws groundwater, free product, and soil gas in the same process stream using a single pump. Groundwater is separated from the free product and is treated (when required) and discharged, free product is recovered which can be recycled, and soil gas vapor is treated (when required) and discharged. A test plan and technical protocol document has been developed for Air Force bioslurping projects (Battelle, 1995).

The following are the significant features of bioslurping:

- *Enhances free-product recovery via vacuum-enhanced pumping*
- *Simultaneously treats vadose zone soils via bioventing*
- *Reduces ratio of groundwater extracted per gallon of fuel recovered compared to conventional dual-pump recovery systems*
- *Can be designed to dewater to expose contamination below the water table (at sites where water table fluctuations occur) or to achieve hydraulic control*
- *Designed to require only one pump to extract from multiple wells, reducing capital costs compared to dual-pump and skimmer systems*
- *Operation and maintenance much less than conventional free-product recovery systems*
- *Can be applied to greater than maximum theoretical suction lift due to liquid entrapment*
- *Can be easily converted to conventional bioventing system (air injection or extraction) when free-product recovery activities are completed*

Dewatering During Bioventing

Dewatering may be necessary during some bioventing projects depending on the distribution of contaminants relative to the water table. If a significant amount of the contamination at a site is present below the water table due to groundwater fluctuations, dewatering of the site in conjunction with a conventional bioventing system may be necessary to adequately treat these areas. However, conventional dewatering produces a wastewater stream which must be treated. Depending on the type and concentration of contaminants and availability of water treatment capacity, the cost of contaminated water treatment may be significant. Air injection has been used to partially dewater soils, but this application is generally limited to low permeability soils.

Moisture, Nutrient, or Microorganism Addition

Traditionally, implementation of a bioremediation system has often involved detailed laboratory treatability studies to determine whether microorganisms are present that can metabolize the contaminant, and to determine whether parameters such as moisture or nutrient addition can increase biodegradation rates. At fuel-hydrocarbon contaminated sites, it is likely that hydrocarbon-degraders will be found, because hydrocarbons are naturally-occurring compounds. Addition of microorganisms *in situ* is commonly suggested; however, few substantial data exist to demonstrate that inoculation of microbes provides any significant improvement in biodegradation over naturally occurring microorganisms. In a laboratory setting, moisture and nutrient addition generally improves biodegradation rates. However, implementation of nutrient addition in the field often is difficult and generally has been found to be unnecessary (Miller, 1990). Moisture addition can at times be beneficial in the field, especially in extreme climates where soil moisture content may be very low (<5%).

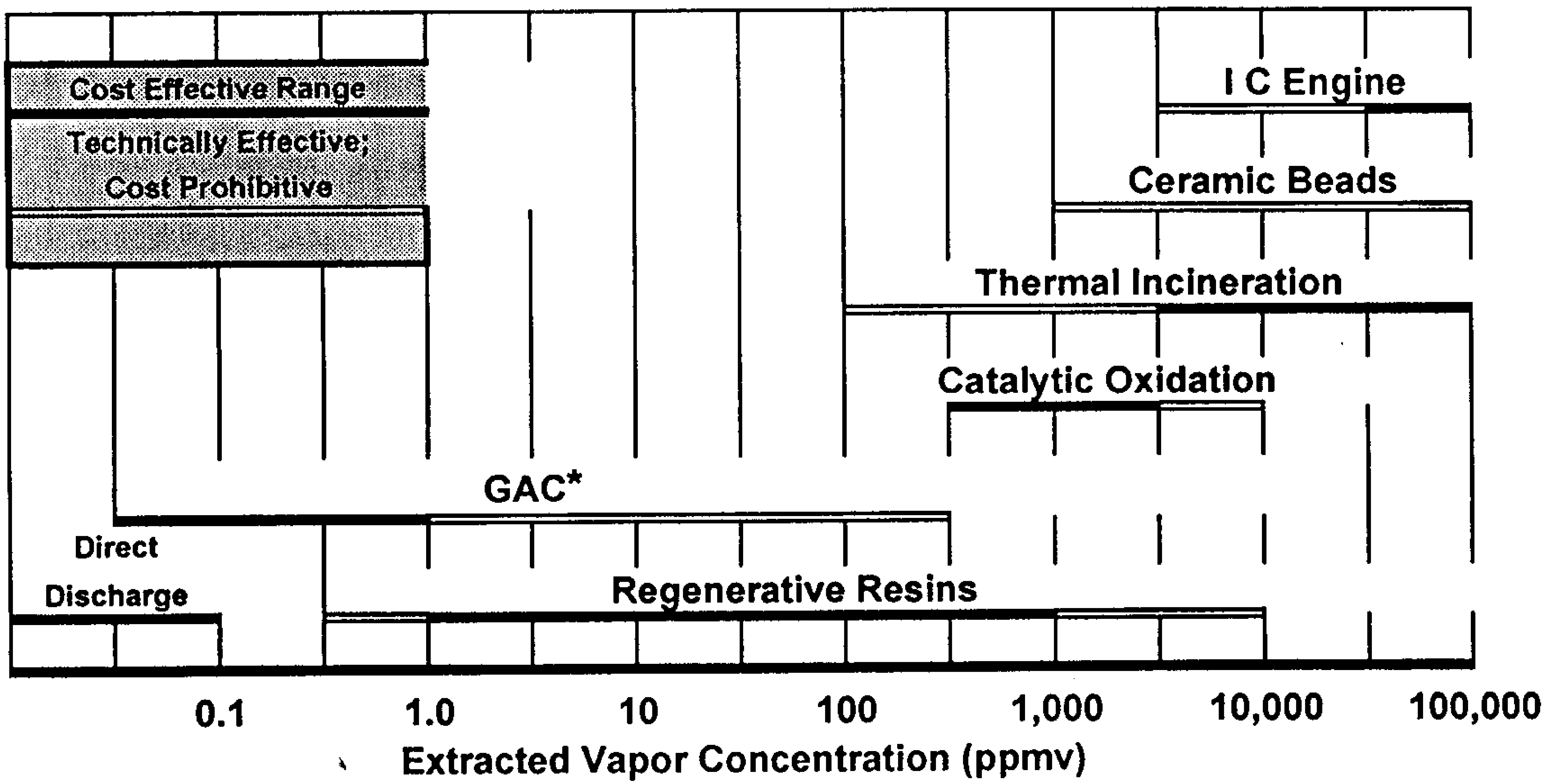
Off-Gas Treatment

Bioventing uses low air-flow rates to minimize volatilization, however, off-gas treatment may still be appropriate for some bioventing applications. Where high soil gas concentrations are of concern, air extraction is recommended as the initial phase of treatment until removal of volatiles has progressed to the stage at which air injection can be initiated. The extracted air may require treatment prior to discharge to remove or destroy contaminants. Treatment is particularly likely to be needed at the start of operations, when the organic vapor concentration in the off-gas is highest. The following subsections discuss minimization of the off-gas flow rate, some commercially available alternatives for treating organic vapors in an air stream, and some emerging vapor treatment technologies (AFCEE, 1992a; AFCEE, 1994; USEPA, 1991b). Figure 8-1 shows the general ranges of applicability for some commonly used off-gas treatment methods. Many of these methods have been used in industrial applications to control point source VOC emissions. Figure 8-1 shows that most of these alternatives may be used over a range of concentrations that spans several orders of magnitude. Usually, however, each option is cost effective over a small part of that range.

Options for organic vapor treatment:

- Limiting off-gas production
- Direct discharge to the atmosphere
- Oxidation methods
    - Flaring direct discharges
    - Flame incineration (direct thermal combustion) - Thermox
    - Catalytic oxidation - Catox
    - Flameless oxidation (packed bed thermal treatment) - Retox
    - Internal combustion - ICE
- Adsorption
    - Carbon (GAC)
    - Resin
- Biodegradation
    - Off-gas reinjection
    - Biofiltration
    - Biotrickling filter
- Emerging vapor treatment technologies

Figure 8-1
Applicability of Vapor Treatment Options



* *GAC can be cost effective at higher concentrations if minimal flow rates are used.*

Limiting Off-Gas Production

Design and operating features can be used to minimize the volume of off-gas released by bioventing systems. This source reduction approach to pollution prevention can be used whenever possible at bioventing sites. Options of minimizing off-gas production include using the lowest air flow rate possible while still supplying sufficient air and/or using air injection instead of air extraction configurations to aerate the contaminated area. Air injection systems are preferred unless site logistics require air extraction to control movement or accumulation of contaminant vapors.

Direct Discharge to the Atmosphere

Off gas containing organic vapors can be released directly through an extraction stack, which will provide dispersion of the vapors but no removal or destruction of contaminants. This may be feasible if VOC concentrations are lower than air treatment standards. The concentration of the contaminants, the off-gas release rate, and the density, location, and type of nearby receptors are considered when evaluating direct discharge options.

Flaring Direct Discharges

It may be feasible to simply light the offgas and letting it burn, as long as the vapor concentrations exceed the lower explosive limit (LEL) of the product. Achieving complete combustion and maintaining the flame can be difficult.

Flame Incineration (Direct Thermal Combustion)

Using a process of high temperature direct thermal combustion, sometimes referred to as flame incineration, can produce rapid oxidation of organic contaminants. When operated with an adequate temperature and residence time, this type of treatment will thermally oxidize (Thermox) hydrocarbon contaminants to carbon dioxide and water. For most contaminants, acceptable contaminant destruction efficiency is achieved with an operating temperature in the range of 1,400 to 1,600 °F and a residence time of 1 second (AFCEE, 1992a). The destruction of the contaminants is a major advantage of this technique over carbon adsorption, which only concentrates the contaminants onto the carbon, which must then be regenerated or disposed. However, direct thermal combustion is not appropriate for influent vapor streams containing chlorinated compounds, because complete combustion of these compounds will generate corrosive hydrochloric acid vapors. The capital cost of a flame incinerator is typically less than that of a catalytic incinerator. However, due to the higher operating temperature, the fuel use will be higher in a flame incinerator. Flame incineration is generally favored over catalytic oxidation when the combustible organic vapor concentration is higher than about 1,000 to 5,000 ppmv (AFCEE, 1992a).

Catalytic Oxidation

Catalytic oxidation (Catox) is an incineration process of vapor treatment in which the vapor stream is heated and passed through a combustion unit where the gas stream contacts a catalyst. The catalyst increases the oxidation reaction rate by adsorbing the contaminant molecules on the catalyst surface. The active catalyst material is typically a precious metal (e.g., palladium or platinum) that provides the surface conditions needed to facilitate the transformation of the contaminant molecules into carbon dioxide and water. The main advantage of catalytic oxidation versus thermal (flame) incineration is the much lower temperature required with a catalyst (600 to 900 °F versus 1,400 °F or higher). Also, the presence of the metal catalyst reduces the supplemental fuel requirements (which can be electrical or natural gas/propane) making this technology more cost effective. Careful monitoring or extraction gas concentration and reactor temperature is required to prevent overheating of the catalyst. Off-gases containing chlorinated compounds tend to deactivate the catalyst, however new technologies potentially capable of treating chlorinated compounds by catalytic oxidation currently are under development and are beginning to become available on the market (Trowbridge and Malot, 1990; Buck and Hauck, 1992). A catalytic oxidation unit for treatment of 100 cfm off-gas flow would have a capital cost in the approximate range of $40,000 to $60,000 (in 1991 dollars) (AFCEE, 1992a).

Flameless Oxidation (Packed Bed Thermal Treatment)
Packed bed thermal treatment, known as flameless oxidation, oxidizes organic contaminants by passing the off-gas stream through a bed of ceramic beads or gravel that is heated by electricity to a temperature of about 1800^{o}F to combust the vapors. This technology has been used to destroy vapor contaminants in the off-gas from several chemical and other industrial plants. The treatment unit is known as a Regenerative Thermal Oxidizer (Retox) unit. The vendor of this technology currently is investigating its applicability to the remediation market (USEPA, 1991b).

Internal Combustion
Internal combustion engine (ICE) treatment accomplishes destruction of organic contaminants by oxidation in a conventional engine. The engine used is an ordinary industrial or automotive engine fueled by propane or natural gas, and its carburetor is modified to accept vapors rather than liquid fuel. Ambient air is bled into the engine to maintain the required oxygen concentration, because off-gas at fuel hydrocarbon sites is often oxygen depleted. A catalytic converter provides discharge treatments to meet requirements of many regulatory agencies. ICEs have been used for years to destroy landfill gas, however application of ICEs to destruction of hydrocarbon vapors in off-gas streams is more recent; the first operational unit was installed in 1986. ICEs are capable of destruction efficiencies of well over 99% (USEPA, 1991b), and are especially useful for treating vapor streams with high concentrations of TPH (up to 30% volume) to levels below 50 ppm. Tests of BTEX destruction show that nondetectable levels of contaminants can be achieved in the outlet off-gas in some cases and outlet concentrations below 1 ppm can be achieved in many cases. ICEs can handle off-gases with high concentrations of organic contaminants which provides a significant advantage over incineration units. On gasoline and JP-4 jet fuel sites, ICEs have treated inlet concentrations as high as 40,000 ppmv and achieved 99 percent destruction (AFCEE, 1994).

Adsorption on Carbon (GAC)
Carbon adsorption is the most commonly used vapor phase treatment method. Systems typically consist of the extracted off-gas moving through one or more sealed vessels filled with granular activated carbon (GAC) that are connected in series and/or parallel. The spent carbon is disposed as a waste when the weight of the captured VOCs equals about 15 to 20 percent of the carbon weight, and is replaced or recycled (reactivated) off-site. GAC is probably the most cost effective organic vapor treatment method for a wide range of applications due to its relative ease of implementation and operation, its established performance history in commercial applications, its ability to be regenerated for repeated use, and its applicability to a wide range of contaminants at a wide range of flow rates. However, carbon adsorption is economical only for lower mass removal rates, and systems are also adversely effected by high vapor moisture levels and high temperatures.

Adsorption on Resin
Specialized resin adsorbents have been developed and are now entering commercial application for treatment of organic vapors in off-gas streams. These synthetic resin adsorbents (synthetic polymer) have a high tolerance to water vapor (unlike GAC) and are amenable to regeneration on site. Skid modules are available consisting of two resin adsorbent beds. The design allows one bed to be on-line treating off-gas while the other bed is being regenerated by a desorption process. During the desorption cycle, all of the organic contaminants trapped on the resin are removed (volatilized), condensed, and transferred to a storage container. Purus, Inc. of San Jose, California has developed an innovative regenerative resin

system, known as PADRE™, which is particularly suited for combination with *in situ* bioventing. This combination of technologies was recently demonstrated sucessfully at a gasoline-contaminated site at Vandenburg AFB, California (Downey et al., 1995). Treated effluent from the PADRE™ unit was recirculated through the soil using a series of perimeter air reinjection or biofilter trenches. Following approximately 16 weeks of soil vapor extraction, average influent VOC concentrations were reduced from over 8,000 ppmv to less than 1,000 ppmv.

Off-Gas Reinjection

Reinjection of off gas for further biodegradation can be a cost-effective and environmentally sound treatment option. This option consists of distributing extracted air with contaminant vapors back into the soil to allow *in situ* aerobic biodegradation to destroy the contaminants. *In situ* respiration and soil-gas permeability data must be available for the site, because these data indicate the expected biodegradation rate and radius of influence which are needed to determine the design capacity for the reinjection point. The system should be configured in a recirculation mode where the potential for vapor migration is mitigated by placing reinjection wells within the zone of capture of the extraction well(s). The available soil volume must be sufficient to accept the off-gas air flow and allow biodegradation of the contaminant mass flow in the off-gas. After reinjection is established, surface emission testing must be performed to ensure contaminants are not escaping at the site surface.

Biofiltration

Instead of burning or trapping hydrocarbon vapors, biofiltration can be used to destroy a variety of VOCs in an off-gas stream by degrading the contaminants to carbon dioxide and water. The biofiltration process uses a large population of microorganisms immobilized as a biofilm on a porous filter substrate (biomass) such as peat or compost. As the air and vapor contaminants pass through the filter, contaminants transfer from the gas phase to the biolayer where they can be metabolized. This technology was originally developed for odor control in Europe. Biofilters can successfully remove over 90 percent of aromatics (e.g. benzene) but perhaps only 50 percent of aliphatic VOCs. Vendor data indicate that biofiltration is most effective for gasoline hydrocarbon vapor concentrations in the range of 50 to 5,000 ppmv (USEPA, 1994). Recent studies by AFCEE indicate that the upper concentration limit for cost-effective treatment may be less than 1,000 ppmv (AFCEE, 1994). It appears in recent test cases that an increased treatment capacity can only be achieved through significant increases in treatment-bed volume. Biofilters are generally not used as a stand-alone technology. Generally, carbon is needed as a post-treatment (polishing) step.

Biotrickling Filter

This type of filter is similar to the biofilter technology described above, except a biotrickling filter implements bacteria-containing water that is circulated counter-current to the offgas stream over a packing material (plastic rather than organic). A biofilm layer forms on the plastic packing material and provides the site of biodegradation. Biotrickling filters generally have better VOC removal efficiencies than biofilters and can usually treat higher influent concentrations. As with biofiltration, biotrickling filters generally need carbon as a post-treatment (polishing) step.

Emerging Vapor Treatment Technologies

Several emerging technologies for destruction or concentration of organic contaminants in an off-gas stream are now being consideredPhotocatalytic oxidation is a treatment method where VOCs entering a photocatalyst unit are converted to carbon dioxide and water (and hydrogen chloride gas and/or chlorine in the case of chlorinated VOCs) by exposure to UV light, and the contaminants are rapidly oxidized. Only 0.2 seconds residence time is required for 95 to 99% destruction efficiency (Kittrel et al., 1995). Gas semipermeable membrane systems are available to concentrate dilute organic vapor streams. The membrane systems do not destroy the organic contaminants, and would be used as a pre-treatment process. The contaminants are trapped on the membrane and can then be condensed and collected or destroyed (USEPA, 1994).

Additional Monitoring Options

The following topics are not parameters that are essential to the operation of a bioventing system. However, these parameters provide supplemental information that can be used to confirm microbial activity, or, in the case of soil temperature monitoring, may provide insight into factors affecting the bioremediation process.

Soil Temperature Monitoring

Microbial activity may result in soil temperature increases. Seasonal changes in soil temperature can affect microbial activity (Leeson et al., 1993; Miller, 1990). Therefore, soil temperature can be monitored with thermocouples attached to soil gas monitoring points. If microbial respiration rates are more or less than expected, soil temperature data are useful as a means of identifying one factor which could be affecting the respiration rates. However, it is unlikely that soil temperature data will be essential for bioventing system operation.

Stable Carbon Isotope Monitoring

Measurement of stable carbon isotope ratios may help substantiate biodegradation. Carbon dioxide produced by hydrocarbon degradation may be distinguished from that produced by other processes based on the carbon isotopic compositions characteristic of the source material and/or the fractionation accompanying microbial metabolism (Leeson and Hinchee, 1995). Carbon dioxide generated from natural organic material has a $\delta^{13}C$ of approximately -10 to -15, whereas carbon dioxide generated from petroleum hydrocarbons has a $\delta^{13}C$ of approximately -20 to -30.

Measurement of Internal Petroleum Biomarkers

Certain chemical indicators of petroleum and refined products may be used to evaluate the degree of biodegradation (Leeson and Hinchee, 1995). This is based on the theory of selecting a component of the petroleum that is highly resistant to microbial attack or weathering. As the petroleum product is degraded, the proportion of this component increases relative to other components. The use of such indicators is dependent on the following assumptions: the source of the oil contamination is a single source; the source of the chemical indicator is not a product of weathering or biodegradation; the chemical indicator is not degraded during weathering; and, the extraction efficiency of the chemical indicator is the same as that of the rest of the oil.

Section 9
PERFORMANCE MONITORING AND PROCESS EVALUATION

Performance Monitoring

Each bioventing removal action will be reviewed periodically to determine if it meets the principle objective for the removal action - early risk reduction by removing a significant quantity of fuel hydrocarbons (including BTEX) from soils in the vadose zone, intercepting an exposure pathway, or preventing additional flux to groundwater. The following subsections discuss methods of tracking the performance of bioventing systems over time, including soil gas sampling, *in situ* respiration (ISR) testing, surface emissions measurement, and operations and maintenance of the bioventing system. In addition, bioventing removal actions generate cost and performance data, which are evaluated to identify design and operational improvements and to establish a basis for final cleanup levels.

Soil Gas Monitoring

Periodic soil gas monitoring is conducted to ensure that the bioventing site is well-oxygenated. Once full aeration is achieved, the bioventing system operation efficiency can be optimized to maintain full oxygenation. After this point, soil gas monitoring is normally conducted at least semiannually for the first year and annually thereafter.

In Situ Respiration (ISR) Testing

ISR testing is conducted periodically as a means of monitoring the progress of site remediation. As the site remediation progresses and contaminant concentrations are reduced, ISR rates should approach those measured in the uncontaminated area. ISR tests are normally conducted semi-annually or quarterly for the first year and annually or semi-annually thereafter. During system operation, an ISR test is conducted by turning the bioventing system off and monitoring soil gas to measure oxygen disappearance (O_2-utilization rate) and carbon dioxide production. Air can also be injected into individual vapor monitoring points as done during initial pilot testing and the O_2-utilization rate measured. The two O_2-utilization rates can be compared and biodegradation rates can be calculated.

ISR rates can be expected to vary with time. A decrease in these rates over time can be an indicator of hydrocarbon biodegradation and contaminant removal and is expected as the contaminant concentrations are reduced during venting. It also may be a function of reduced bioavailability as more mobile and soluble contaminants are preferentially biodegraded leaving less soluble fuel hydrocarbons in the vadose zone soils. Long-term bioventing treatability studies have shown that as hydrocarbons are reduced to lower concentrations, O_2-utilization rates decrease to rates that are approximately the same as in clean background soils (Stanin and Phelps, 1994).

Quantification of Biodegradation and Volatilization of Hydrocarbons

If the bioventing system implements air extraction, the amount of hydrocarbons biodegraded and volatilized can be estimated through direct measurement of off-gas concentrations of oxygen and carbon dioxide (Section 7). Reconfiguration of an injection system to extraction mode in order to estimate biodegradation and volatilization amounts will provide an overestimate of the mass of hydrocarbons volatilized, because the size of the *in situ* biologically active zone is reduced (Leeson and Hinchee, 1995).

The fraction of total contaminant removal by biodegradation will be larger for injection systems because the opportunity for biodegradation is greater. In injection mode, the vapors are pushed through the contaminated zone into the uncontaminated zone, allowing for additional biodegradation as the treatment zone in effect increases geometrically in size. Injection also results in the highest concentration of oxygen delivered to the more highly contaminated zone. However, when the system is operated in extraction mode, much of the vapor is removed from the soil before biodegradation can occur. Also, air extraction pulls air from the perimeter and oxygen levels can be reduced in transit through the highly contaminated zone. "Typical" hydrocarbon removal rates due to biodegradation and volatilization as a function of the air flow rate for both injection and extraction modes are shown in Figures 9-1 and 9-2.

Figure 9-1. Hydrocarbon Volatilization and Biodegradation Rates as a Function of Air Flow Rate During Air Injection

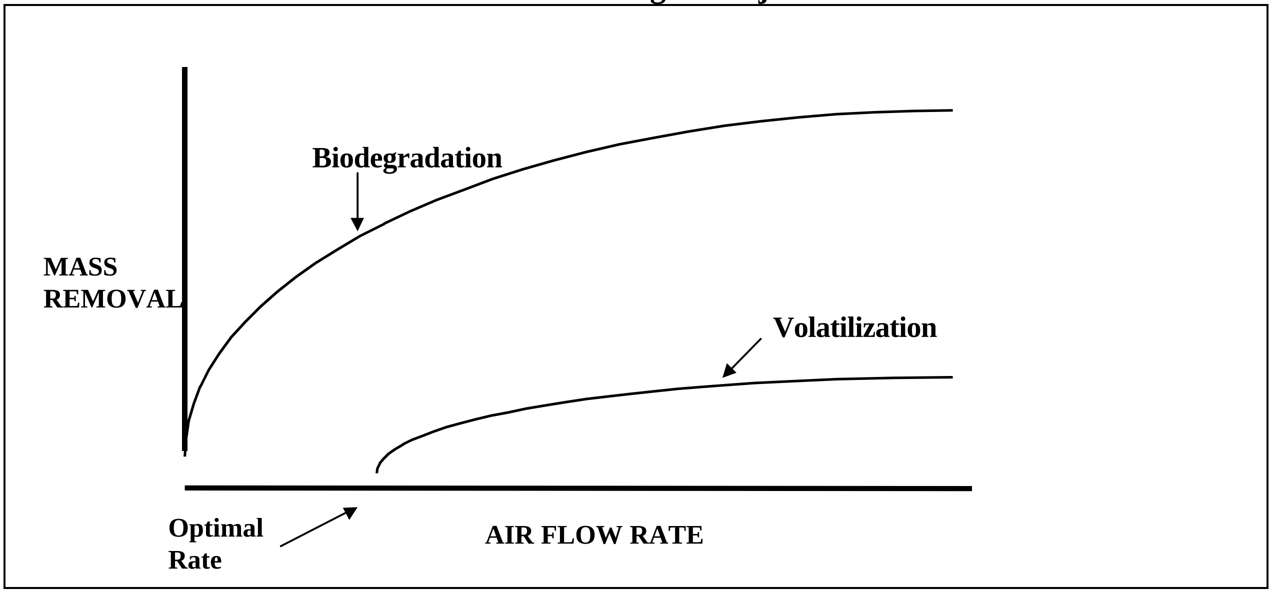
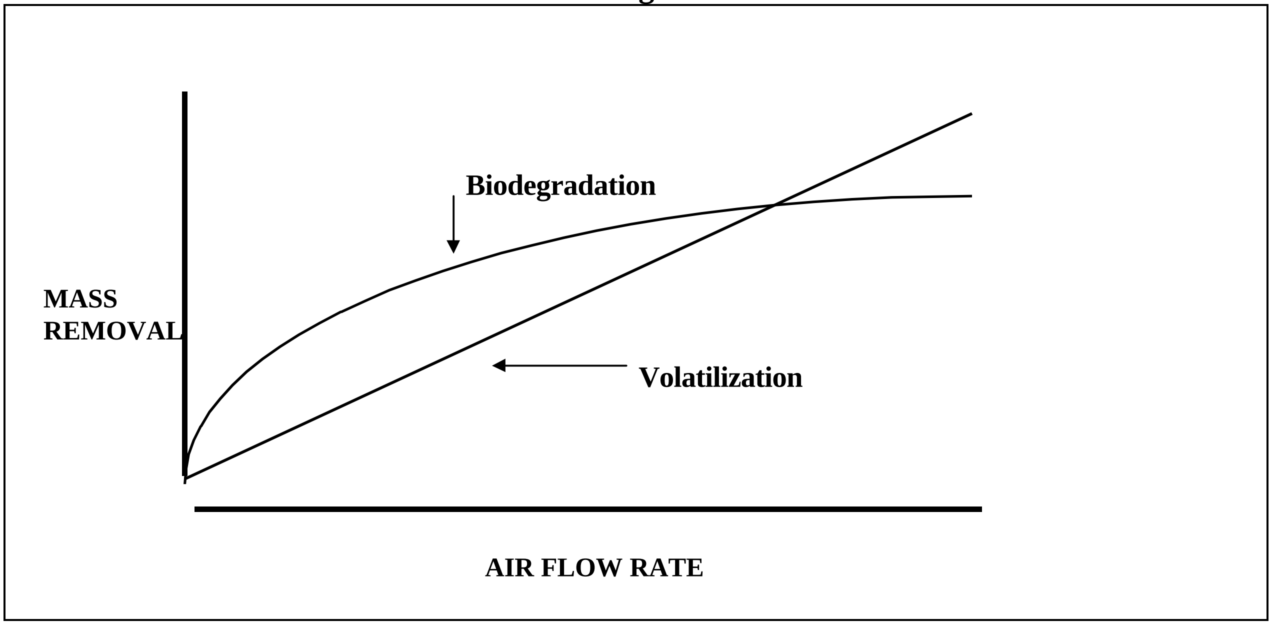


Figure 9-2. Hydrocarbon Volatilization and Biodegradation Rates as a Function of Air Flow Rate During Air Extraction



Surface Emissions Sampling

Although surface emissions typically do not occur or are at very low at bioventing sites due to low air flow rates, possible surface emissions often are a regulatory concern and surface emission rates may need to be quantified in order to obtain regulatory approval for bioventing. However, it should be noted that according to the US EPA document *Estimation of Air Impacts for Bioventing Systems Used at Superfund Sites* (EPA 451/R-93-003), emissions from bioventing sites operating in injection mode are thought to be minimal. One standard surface emission sampling protocol using isolation flux chamber procedures is described by the USEPA (USEPA, 1986). The actual emission rates of organic compounds from the soil surface into the atmosphere is calculated from the field data. At bioventing sites where surface emissions have been measured, surface emission rates of BTEX and TPH have been several orders of magnitude below regulatory levels (Leeson and Hinchee, 1995). These results have provided strong support for continued operation of bioventing systems in injection mode. Results of surface emission measurements (flux monitoring) from the Bioventing Initiative Project were given in Section 4.

Operation and Maintenance

Bioventing systems are very simple, with very minimal mechanical and electrical parts. If the system is operated in injection mode, a simple visual system check to ensure that the blower is operating within its intended flow rate, pressure, and temperature range would be required. If an extraction system or an extraction/reinjection bioventing system is installed, more intensive maintenance is likely to be required.

Process Evaluation and Site Closure

In Situ Respiration (ISR) Testing

A good indication that the site may remediated and that final (confirmatory) soil sampling can be conducted is when the *in situ* respiration rate (oxygen utilization rate) in contaminated soils are similar to that in uncontaminated soils. ISR testing used in this way is economically significant, because soil sampling is not relied upon as the sole indicator of site remediation and the high cost associated with intermediate soil sampling can be eliminated. Initially, ISR tests are used to estimate the amount of time necessary for cleanup of a site. This calculation provides a reasonable “ball park” estimate, however, the calculation must be coupled with process monitoring (periodic ISR testing) to provide field-based evidence that the site may actually be remediated within the initial time estimate. Due to the heterogeneity of sites, the average biodegradation rate calculated from ISR test data does not reflect actual biodegradation rates throughout the site. Biodegradation rates also may fluctuate with season and as contaminant concentrations decrease. Therefore, periodic process monitoring is an important parameter in determining treatment time.

Soil Sampling

Soil sampling is not used as a process monitoring technique, because the goal of soil sampling is to *confirm cleanup,* and not to periodically monitor progress in contaminant reduction as done by ISR testing. This strategy is justified because the number of samples required to produce a meaningful result is prohibitive until contamination levels approach 90 to 99% cleanup due to the inherently high variability of fuel hydrocarbons in soils at a contaminated site. Also, the amount of soil sampling conducted at a site has a tremendous impact on the cost of the project. Minimizing soil sampling will make a remediation effort much more cost effective. Therefore, as previously discussed, ISR testing can indicate when a site is clean and when to collect confirmatory soil samples.

The number of final soil samples collected is usually driven by regulatory issues, and local regulatory agencies should be contacted before developing a final sampling plan. The Department of Natural Resources of the State of Michigan has established guidance for verification of soil remediation. This guidance provides several methods for statistical sampling strategies and provides information on design of the sampling grid and determination of the upper confidence limit (UCL) of the final mean. An alternative method for estimating final sample size is provided by Ott (1984). This method determines the required number of soil samples to show a statistical difference between initial and final contaminant concentrations.

Site Closure

Since acceptable soil cleanup levels are usually site-specific, bioventing systems are likely to continue to operate until such decisions are made. The major factors affecting bioventing performance are determined, enhancements to improve the efficiency of the bioventing system are considered, and system modifications are implemented so that consistent performance of the system can eliminate predictive modeling. As a bioventing removal action proceeds, performance and cost data are evaluated to establish a basis for final cleanup levels. Once soil cleanup levels are established, bioventing removal actions may transition into a final remedy for fuel hydrocarbon contamination at the site. A site is considered to be fully remediated if soil fuel-hydrocarbon concentrations remain below cleanup levels after the termination of bioventing operations.

Section 10
RISK-BASED REMEDIATION -- BIOVENTING REMOVAL ACTIONS INTEGRATED WITH INTRINSIC REMEDIATION

Risk-Based Remediation

As presented in Section 5, risk-based corrective action (RBCA) has been developed to provide a technically defensible, consistent, multi-tiered, exposure/risk-based assessment methodology which provides a strong basis for site-specifically determining site classification and initial response, cleanup goals, and corrective action for soil and groundwater. If a risk-based approach to soil cleanup is used (focusing on removing the soluble, mobile, and more toxic BTEX constituents of fuels rather than TPH levels), soil remediation times can be significantly reduced. This is a reasonable and practical approach, especially because bioventing has been demonstrated in recent studies (Miller et al., 1993; Section 4) the ability of preferential removal of benzene and other aromatics (BTEX). This is important because the BTEX components of fuels are of most concern when considering groundwater contamination. Therefore, once bioventing has successfully removed these contaminants of concern from the soil, a risk-based approach to any groundwater contamination that may be present at the site can be implemented. To implement this strategy, a technical protocol document for implementation of the intrinsic remediation/long-term monitoring option for the natural attenuation of fuel contamination was developed for the US Air Force in cooperation with United States Environmental Protection Agency (EPA) researchers (Wiedemeier, et al., 1995). The risk-based approach for implementing intrinsic remediation is outlined in Figure 10-1 and is discussed below.

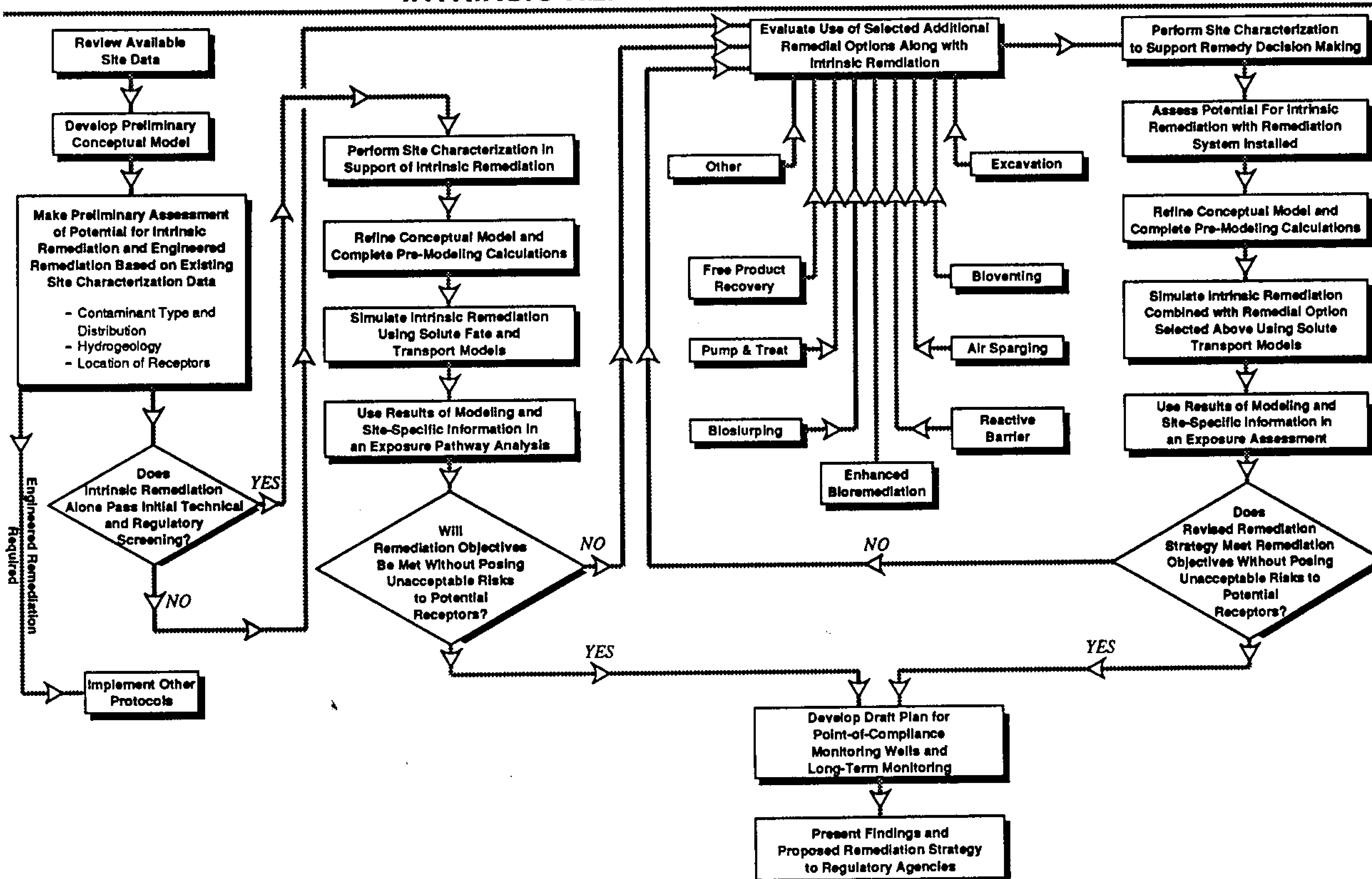
Intrinsic Remediation

As discussed throughout this General Evaluation Document, fuel-hydrocarbon contamination in vadose zone soils can be biologically remediated with *in situ* bioventing. The Bioventing Initiative Project has shown this is possible without the addition of organisms, nutrients, surfactants, or other microbial respiratory substrates. If oxygen is all that is needed in the vadose zone to enhance the natural biodegradation process, then it follows that oxygen and other potential electron acceptors (NO_3, Fe^{3+}, Mn^{3+}, SO_4, CO_2) in the saturated zone should stimulate biodegradation of dissolved fuel components in groundwater such as BTEX. The only question is how fast and how far the BTEX plume will migrate before the microorganisms, together with volatilization and adsorption, can stop it. The answer is dependent on the reservoir of electron acceptors available in the groundwater and site-specific biodegradation rates.

Principles
Uncontaminated groundwater in aquifer material with low organic content contains dissolved oxygen in concentrations from about 1 to 7 mg/L. Based on EPA sponsored research, there is no dissolved oxygen in the center of BTEX groundwater plumes because the natural microorganisms have consumed it in the process of degrading the fuel hydrocarbons. As oxygen is consumed, anaerobic degradation processes begin to dominate as NO_3, Fe^{3+}, Mn^{3+}, SO_4, and CO_2 are used as alternate electron acceptors by anaerobic microorganisms. These alternate electron acceptors can be significant due to their higher respective solubilities in water compared to that of oxygen. As the plume disperses, retards, and biodegrades with respect to groundwater flow, the edges of the plume become less and less concentrated with BTEX. When the flux of contaminants and dissolved electron acceptors on the perimeter reach equilibrium, the plume will reach steady-state conditions and will stop migrating (AFCEE, 1992b).

FIGURE 10-1

INTRINSIC REMEDIATION FLOW CHART



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Intrinsic remediation is achieved when naturally occurring attenuation mechanisms (aerobic and anaerobic biodegradation) bring about a reduction in the total mass of a dissolved contaminant (BTEX) in groundwater. In some cases, intrinsic remediation will reduce dissolved-phase contaminant concentrations to below MCLs before the contaminant plume reaches potential receptors. In situations where intrinsic remediation will not reduce contaminant concentrations to below regulatory MCLs, reasonable risk-based cleanup goals may be implemented if it can be demonstrated that intrinsic remediation will result in a continual reduction in contaminant concentrations over time such that long-term risks are controlled and reduced.

Source Removal With Intrinsic Remediation

When the source of BTEX is removed, the dissolved BTEX groundwater plume will recede naturally. This natural attenuation of the plume is termed intrinsic remediation. The source removal is accomplished by floating product removal (Section 8), and by removing residual fuel hydrocarbons from the vadose zone soils by bioventing. Therefore, bioventing as an active source removal action (and floating product removal if necessary), and monitoring the natural attenuation of BTEX groundwater plumes, can be implemented as a complete tool for managing fuel-contaminated sites.

Advantages and Disadvantages

The implementation of intrinsic remediation as a site strategy has several advantages over other more active remediation methods. The advantages focus on the method's non-intrusive nature and relative low cost.

Advantages of intrinsic remediation include:

- Contaminants are transformed to innocuous byproducts (e.g., CO_2 and water) instead of just being transferred to another phase or location in the environment.
- The method is non-intrusive and allows continuing use of infrastructure during remediation.
- Current remedial technologies can pose greater risk to potential receptors than intrinsic remediation because contaminants may be transferred into the atmosphere during remediation activities.
- The method is less costly than conventional remedial technologies such as pump-and-treat.

The main limitation of intrinsic remediation is that it is subject to natural and institutionally-induced changes in local hydrogeologic conditions and local land use. In addition, aquifer heterogeneity may complicate site characterization as it will with any remedial technology.

Intrinsic Remediation Projects

The Robert S. Kerr Environmental Research Laboratory (RSKERL) of the USEPA sponsored the first work in modeling the natural attenuation of BTEX in groundwater. The model used was Bioplume II^{TM} that was developed by Rice University who markets the model for the USEPA. Several environmental consulting firms are now completing natural attenuation studies using this model. The American Petroleum Institute (API) is also investigating natural attenuation as the answer to groundwater remediation at thousands of oil company-owned sites. Emerging research by USEPA's Environmental Monitoring Surveillance Laboratory (EMSL) with USEPA's Office of Underground Storage Tanks (OUST), and Utah State University researchers, is in the process of investigating the idea that product removal and soil treatment are often unnecessary for nature to fully contain, and protect public health from, contamination at fuel-contamination sites.

A joint effort of the Air Force Center for Environmental Excellence-Technology Transfer Division (AFCEE), the Bioremediation Research Team at USEPA's RSKERL, and Parsons Engineering Science is implementing a program of intrinsic remediation studies (Natural Attenuation Initiative) at fuel-hydrocarbon contaminated sites owned by the Air Force and other US Department of Defense (DOD) agencies, the US Department of Energy (DOE), and public interests. To facilitate this program, a comprehensive protocol document was developed (Wiedemeier, et al., 1995). This document describes intrinsic remediation processes, site characterization activities that may be performed to support the intrinsic remediation option, intrinsic remediation modeling using simple analytical and numerical fate and transport models such as Bioplume II^{TM}, and the post-modeling activities that should be completed to ensure successful support and verification of intrinsic remediation.

Implementation of Intrinsic Remediation

To support implementation of intrinsic remediation, the property owner must scientifically demonstrate that degradation of site contaminants is occurring at rates sufficient to be protective of human health and the environment. Three lines of evidence can be used to support intrinsic remediation including:

- Documented loss of contaminants at the field scale
- The use of chemical analytical data in mass balance equations
- Laboratory microcosm studies using aquifer samples collected from the site

This evidence is acquired by:

- Site characterization activities and aquifer parameter estimations for conceptual model refinement
- Analytical and numerical modeling
- Exposure assessment
- Long-term monitoring

Site Characterization

Collection of an adequate database during the iterative site characterization process is an important step. This phase should provide data on the location and extent of contaminant sources and dissolved-phase contamination; groundwater geochemical data; geologic information on the type and distribution of subsurface materials; and hydrogeologic parameters such as hydraulic conductivity, hydraulic gradients, and potential contaminant migration pathways to human or ecological receptors.

Analytical or Numerical Modeling

Data collected during site characterization activities can be used to model the fate and transport of contaminants. Such modeling allows prediction of the future extent and concentration of the dissolved-phase plume. Several models, including simple analytical models (Buscheck and Alcantar, 1995) and Bioplume II^{TM} (Rifai et al., 1988) have been used successfully to model dissolved-phase contaminant transport and attenuation. Bioscreen^{TM} is an easily implemented spreadsheet model based on the Domenico analytical solute transport model that simulates natural attenuation of dissolved hydrocarbons (Domenico and Robbins, 1985; Domenico, 1987). It is designed to complement the new Bioplume III^{TM} biodegradation model, and both together are now being tested as part of AFCEE's Natural Attenuation Initiative. The intrinsic remediation modeling effort has three primary objectives:

- Predict the future extent and concentration of a dissolved-phase contaminant plume by modeling the combined effects of advection, dispersion, sorption, and biodegradation
- Assess the possible risk to potential downgradient receptors
- Provide technical support for the natural attenuation remedial option at post-modeling regulatory negotiations

Exposure Assessment

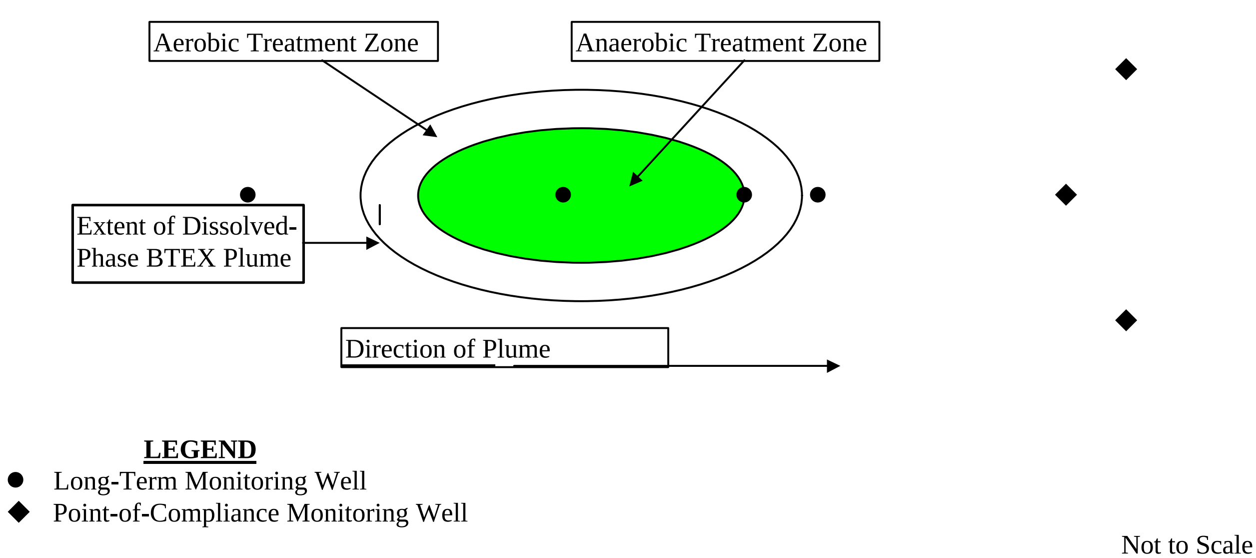
Fate and transport model predictions can be used in an exposure assessment. If intrinsic remediation is sufficiently active to mitigate risks to potential receptors, the proponent of intrinsic remediation has a reasonable basis for negotiating this option with regulators. The exposure assessment allows the proponent to show that potential exposure pathways will not be completed.

Long-Term Monitoring

Groundwater monitoring wells are installed and sampled to document intrinsic remediation of dissolved contaminants. Most of the wells installed during the site investigation phase are used for long-term monitoring. Required are one well upgradient of the contaminant plume, one well within the anaerobic treatment zone, one well in the aerobic treatment zone, and one well immediately downgradient of the plume. In addition, point-of-compliance (POC) monitoring wells are installed downgradient of the contaminant plume and upgradient of potential receptors. POC monitoring wells are generally installed along a property boundary or at a location approximately 5 years downgradient of the current plume (at the seepage velocity of the groundwater) or 1 to 2 years upgradient of the nearest downgradient receptor. Figure 10-2 shows a hypothetical long-term monitoring scenario. This can be thought of as a final snap-shot of a fuel-hydrocarbon contaminated site following a bioventing removal action and follow-up groundwater investigation and modeling.

Figure 10-2

Hypothetical Long-Term Monitoring Strategy Following Bioventing and Intrinsic Remediation Modeling



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APPENDIX A

The Work Group Cost and Performance Information for Selected US Air Force Bioventing Initative Sites

Table A-1a. Site Background, Characteristics, and Treatment Systems.
Hill AFB, Utah: Building 914 Site.

Site Background	Site Characteristics	Treatment Systems
Historical Activity that Generated Contamination Air Transportation, Nonscheduled (SIC Code 4522).	***Media Treated*** Soil.	***Primary Treatment Systems*** Bioventing. Soil Vapor Extraction.
Management Practices that Contributed to Contamination Underground Storage Tanks. Spill at automatic overflow shut-off valve failure (27,000 gal JP-4 released; contaminated approximately 1 acre soil to depth of 50 ft bgs).	***Contaminants Treated*** JP-4 Jet Fuel.	***Supplemental Treatment Systems*** Catalytic Oxidation (SVE off-gas). Biofiltration (SVE off-gas).

Table A-1b. Matrix Characteristics Affecting Treatment Cost or Performance, and Associated Measurement Procedures.
Hill AFB, Utah: Building 914 Site.

Parameter	Value	Measurement Procedure
Soil Types	Mixed coarse sand and gravel deposits with interbedded, discontinuous clay stringers to a confined groundwater table approximately 600 ft bgs.	Visual description of cuttings.
Air Permeability	Not measured.	None.
pH	Not measured.	None.
Porosity	Not measured.	None.
Total Organic Carbon	Not measured.	None.
Total Petroleum Hydrocarbons (TPH)	Maximum 20,000 mg/kg; majority of contamination between 1,000 and 5,000 mg/kg TPH. Contamination unevenly distributed to depth of 50 ft bgs.	Not available.
Non Aqueous Phase Liquids (NAPLs)	Not investigated.	None.

Literature source: Dupont et al. (1991).

**Table A-1c. Operating Parameters Affecting Treatment Cost or Performance.
Hill AFB, Utah: Building 914 Site.**

Parameter	Value	Measurement Procedure
Air Flow Rate	SVE (15 VW s): 26 acfm (initial); 1,500 acfm (final). Bioventing: 350 to 700 acfm.	Not available.
Moisture Content	Initial: 4% to 8% (wt %). After irrigation: 8% to 12%.	Neutron probes.
Operating Pressure/Vacuum	Not available.	Not available.
Temperature	Not measured.	None.
Oxygen Uptake Rate (Mean)	High-rate venting: 0.367 liter per day. Low-rate venting: 0.016 liter per day. Moisture addition: 0.030 liter per day. Nutrient and moisture addition: 0.016 liter per day.	Shutting down venting system followed by monitoring changes in soil gas O_2 content (portable field meter)..
Carbon Dioxide Evolution (Mean)	Low-rate venting: 0.202 liter per day. Nutrient and moisture addition: 0.185 liter per day.	Shutting down venting system followed by monitoring changes in soil gas CO_2 content (portable field meter).
Hydrocarbon Degradation Rate	Biodegradation accounted for 15% to 25% of recovered hydrocarbons.	O2 utilization basis.
Nutrients and Other Soil Amendments	Nutrient concentrations were not measured initially in soils. Moisture and nutrients were later added to site soils.	Addition of culinary water via surface spray irrigation (30 gpm). Addition of ammonium nitrate and sodium triphosphate (C:N:P = 100:10:10) by tilling in dry mix at surface followed by surface spray irrigation (30 gpm).

Literature source: Dupont et al. (1991).

**Table A-1d. Performance Information.
Hill AFB, Utah: Building 914 Site.**

Performance-Related Topic	Relevant Information
Types of Samples Collected	Soil and soil gas (soil gas used to assess the biodegradation component of contaminant mass removal). Samples analyzed for TPH, O_2, and CO_2.
Sampling Frequency and Protocol	Soil samples collected in 15 vent wells at 5-foot intervals from surface to 66 feet. Continuous monitoring of O_2 and CO_2 in soil gas.
Untreated and Treated Contaminant Concentrations	TPH concentrations with depth (average) and TPH removal over time are shown in Figure 4-11.
Comparison with Cleanup Goals	Soil TPH limit of 38.1 mg/kg was set by the Utah Department of Health. Average TPH concentration after treatment was less than 6 mg/kg. The technology was operated to assess the mass removal by both volatilization (SVE) and bioremediation (bioventing).
Analytical Methodology	Identification of methodology not available at this time. No exceptions to standard methodology identified.
QA/QC	Type of QA/QC measures not available at this time. No exceptions to QA/QC protocol or data quality objectives identified.
Other Residuals	None identified for this application.

Table A-1e. Site Remediation Project Costs.
Hill AFB, Utah: Building 914 Site.

Interagency WBS #	Cost Element	Costs ($)
33-01-XX	Mobilization and Prepatory Work	NA
33-02-XX	Monitoring, Sampling, Testing, and Analysis - Lab Analysis of Soil Samples	NA
33-02-XX	Monitoring, Sampling, Testing, and Analysis - Lab Analysis of Soil Gas Samples from Vws and VMPs	NA
33-03-XX	Site Work	NA
33-07-XX	Air Pollution / Gas Collection and Control	NA
33-09-XX	Liquids Collection and Containment (JP-4 jet fuel)	NA
33-10-XX	Tank Demolition and Removal	NA
33-11-XX	Biological Treatment - Gas Reinjection Into Soil	NA
33-11-XX	Biological Treatment - Moisture and Nutrient Addition	NA
33-13-XX	Physical Treatment - Catalytic Oxidation Treatment of Gas	NA
33-19-XX	Disposal (commercial) - Soil Cuttings Disposal	NA
33-21-XX	Demobilization - Post-Construction Submittals	NA
33-9X	Other	NA
	Total Costs:	**NA**

Note: Study conducted 1988-1990. NA = costs not available. XX = third level WBS cost elements not available.

Table A-2a. Site Background, Characteristics, and Treatment Systems.
Kelly AFB, Texas: Site FC-2.

Site Background	Site Characteristics	Treatment Systems
Historical Activity that Generated Contamination DOD-Misc. (SIC Code 1711A).	***Media Treated*** Soil.	***Primary Treatment Systems*** Bioventing (air injection).
Management Practices that Contributed to Contamination Fire training exercises in an unlined pit. Waste petroleum, oils, and lubricants were burned.	***Contaminants Treated*** Petroleum hydrocarbons (non-specific).	***Supplemental Treatment Systems*** None.

Table A-2b. Matrix Characteristics Affecting Treatment Cost or Performance, and Associated Measurement Procedures.
Kelly AFB, Texas: SiteFC-2.

Parameter	Value	Measurement Procedure
Soil Types	Gravelly clay from surface to water table (15 to 18 ft bgs).	Visual description of cuttings. ASTM D422-63 (Laboratory particle size analysis).
Air Permeability	14.7 darcys	Pressure response measurements during air injection (steady-state calculation).
pH	7.8 to 8.9	EPA Method 9045
Porosity	Not measured (45% estimated).	None.
Total Organic Carbon	Not measured.	None.
Total Petroleum Hydrocarbons (TPH)	280 to 3,500 mg/kg at bioventing test site. 9 to 10,000 mg/kg site-wide.	EPA Method 418.1 Not known.
Non Aqueous Phase Liquids (NAPLs)	0.5 to 1.0 ft free product detected in one well (F202) at site.	Water level indicator.

Table A-2c. Operating Parameters Affecting Treatment Cost or Performance.
Kelly AFB, Texas: Site FC-2.

Parameter	Value	Measurement Procedure
Air Flow Rate	48 scfm (injection) into one vent well.	Pitot tube.
Moisture Content	20.1% avg.(initial); 20.0% avg.(final).	ASTM D-2216.
Operating Pressure/Vacuum	3.0 in. H_2O (pressure) at 6 months.	Direct reading (pressure gauge).
Temperature	110^{o}F (blower) at 6 months.	Direct reading (temperature gauge).
Oxygen Uptake Rate	Initial: 0.021-0.040 %/min. 6-mo: 0.0019-0.029 %/min. 1-yr: 0.0023-0.022 %/min.	Point (VMP) test. Area-wide test. Point (VMP) test.
Carbon Dioxide Evolution	Not calculated.	Calculation methodology in protocol document.
Hydrocarbon Degradation Rate	Initial: 5,600 mg fuel/kg soil/yr (avg). 6-mo: 1,700 mg fuel/kg soil/yr (avg). 1-yr: 930 mg fuel/kg soil/yr (avg).	Calculation methodology in protocol document.
Nutrients and Other Soil Amendments	None added.	None.

Protocol document: "Test Plan and Technical Protocol for a Field Treatability Test for Bioventing." R.E. Hinchee et al., May 1992.

Table A-2d. Performance Information.
Kelly AFB, Texas: Site FC-2.

Performance-Related Topic	Relevant Information
Types of Samples Collected	Soil and soil gas (soil gas used to assess the biodegradation component of contaminant mass removal). Soil gas samples analyzed for TPH, CO_2, and O_2. Soil samples analyzed for TRPH, BTEX, moisture content, grain size, and nutrients.
Sampling Frequency and Protocol	Soil samples were collected from one VW and two VMP boreholes at depths of 14 to 15 ft bgs. Soil gas concentrations of TPH, CO_2, and O_2 were monitored periodically throughout one year of pilot testing.
Untreated and Treated Contaminant Concentrations	TRPH and BTEX concentrations in soil and their removal over time are shown in Figure 4-12.
Comparison with Cleanup Goals	Risk Reduction Rule Standard #2 (based on groundwater protection in residential areas) in Texas is non-specific for TPH. Levels for BTEX are 0.5 mg/kg benzene; 100 mg/kg toluene, 70 mg/kg ethylbenzene, and 1,000 mg/kg total xylenes. BTEX concentrations were reduced to concentrations below these standards (Figure 4-12).
Analytical Methodology	Sampling and pilot testing procedures presented in Protocol Document.
QA/QC	Procedures and requirements presented in a Field Sampling Plan and a Quality Assurance Program Plan for the Bioventing Initiative Project.
Other Residuals	None.

Protocol document: "Test Plan and Technical Protocol for a Field Treatability Test for Bioventing." R.E. Hinchee et al., May 1992.

Table A-2e. Site Remediation Project Costs.
Kelly AFB, Texas: Site FC-2.

Interagency WBS #	Cost Element	Costs ($)
33-01-XX	Mobilization and Prepatory Work	5,800
33-02-XX	Monitoring, Sampling, Testing, and Analysis - Lab Analysis of Soil Samples (includes drilling costs).	7,700
33-02-XX	Monitoring, Sampling, Testing, and Analysis - Lab Analysis of Soil Gas Samples from Vws and VMPs	15,300
33-19-XX	Disposal (commercial) - Soil Cuttings Disposal	0
33-21-XX	Demobilization - Post-Construction Submittals	4,600
33-9X	Other (Proj. mgmt.)	3,000
	Total Costs:	**36,400**

XX = third level WBS cost elements not available.

Table A-3a. Site Background, Characteristics, and Treatment Systems.
Battle Creek Air National Guard Base (ANGB), Michigan: Fire Training Area.

Site Background	Site Characteristics	Treatment Systems
Historical Activity that Generated Contamination DOD-Misc. (SIC Code 1711A).	***Media Treated*** Soil.	***Primary Treatment Systems*** Bioventing (air injection).
Management Practices that Contributed to Contamination Fire training exercises in an unlined pit. Estimated 74,000 gallons of jet fuel, waste oils, and hydraulic fuels were burned.	***Contaminants Treated*** JP-4 jet fuel and volatiles, nonhalogenated (BTEX).	***Supplemental Treatment Systems*** None.

Table A-3b. Matrix Characteristics Affecting Treatment Cost or Performance, and Associated Measurement Procedures.
Battle Creek ANGB, Michigan: Fire Training Area.

Parameter	Value	Measurement Procedure
Soil Types	Predominately sandy soil down to water table (30 ft bgs).	Visual description of cuttings. ASTM D422-63 (Laboratory particle size analysis).
Air Permeability	227 darcys	Pressure response measurements during air injection (steady-state calculation).
pH	8.0 to 8.6	EPA Method 9045.
Porosity	Not measured (30% estimated).	None.
Total Organic Carbon	Not measured.	None.
Total Petroleum Hydrocarbons (TPH)	120 to 15,000 mg/kg at bioventing test site. 1.5 to 48,500 mg/kg site-wide.	EPA Method 418.1 RSK SOP-174.
Non Aqueous Phase Liquids (NAPLs)	None detected.	None.

Table A-3c. Operating Parameters Affecting Treatment Cost or Performance. Battle Creek ANGB, Michigan: Fire Training Area.

Parameter	Value	Measurement Procedure
Air Flow Rate	40 scfm (injection) into one vent well.	Pitot tube.
Moisture Content	4.7% avg.(initial); 5.0% avg.(final).	ASTM D-2216.
Operating Pressure/Vacuum	3.0 in. H_2O (pressure) at 6 months.	Direct reading (pressure gauge).
Temperature	70°F (blower) at 6 months.	Direct reading (temperature gauge).
Oxygen Uptake Rate	Initial: 0.002-0.015 %/min. 6-mo: 0.001-0.0048 %/min. 1-yr: 0.0004-0.011 %/min.	Point (VMP) test. Area-wide test. Point (VMP) test.
Carbon Dioxide Evolution	Not calculated.	Calculation methodology in protocol document.
Hydrocarbon Degradation Rate	Initial: 580-3,700 mg fuel/kg soil/yr. 6-mo: 250-1,200 mg fuel/kg soil/yr. 1-yr: 86-2,300 mg fuel/kg soil/yr..	Calculation methodology in protocol document.
Nutrients and Other Soil Amendments	None added.	None.

Protocol document: "Test Plan and Technical Protocol for a Field Treatability Test for Bioventing." R.E. Hinchee et al., May 1992.

Table A-3d. Performance Information. Battle Creek ANGB, Michigan: Fire Training Area.

Performance-Related Topic	Relevant Information
Types of Samples Collected	Soil and soil gas (soil gas used to assess the biodegradation component of contaminant mass removal). Soil gas samples analyzed for TPH, CO_2, and O_2. Soil samples analyzed for TRPH, BTEX, moisture content, grain size, and nutrients.
Sampling Frequency and Protocol	Soil samples were collected from one VW and two VMP boreholes at depths of 8 ft bgs (VW-1), 7 ft bgs (MPA), and 18 ft bgs (MPB). Soil gas concentrations of TPH, CO_2, and O_2 were monitored periodically throughout one year of pilot testing.
Untreated and Treated Contaminant Concentrations	TPH and BTEX concentrations and their removal over time are shown in Figure 4-13.
Comparison with Cleanup Goals	No cleanup goals set for site.
Analytical Methodology	Sampling and pilot testing procedures presented in Protocol Document.
QA/QC	Procedures and requirements presented in a Field Sampling Plan and a Quality Assurance Program Plan for the Bioventing Initiative Project.
Other Residuals	None.

Table A-3e. Site Remediation Project Costs.
Battle Creek ANGB, Michigan: Fire Training Area.

Interagency WBS #	Cost Element	Costs ($)
33-01-XX	Mobilization and Prepatory Work	12,400
33-02-XX	Monitoring, Sampling, Testing, and Analysis - Lab Analysis of Soil Samples (includes drilling costs)	8,600
33-02-XX	Monitoring, Sampling, Testing, and Analysis - Lab Analysis of Soil Gas Samples from Vws and VMPs	17,100
33-19-XX	Disposal (commercial) - Soil Cuttings Disposal	0
33-21-XX	Demobilization - Post-Construction Submittals	9,120
33-9X	Other (Proj. mgmt.)	4,500
	Total Costs:	**51,720**

XX = third level WBS cost elements not available.

Table A-4a. Site Background, Characteristics, and Treatment Systems.
Burlington Northern Railroad Facility, Nebraska: Fueling Pump House.

Site Background	Site Characteristics	Treatment Systems
Historical Activity that Generated Contamination Transportation: Railroads, Line-Haul Operating (SIC Code 4011).	***Media Treated*** Soil.	***Primary Treatment Systems*** Bioventing (via air extraction).
Management Practices that Contributed to Contamination Spill of No. 2 diesel fuel from a ruptured pipe at a fueling pump house.	***Contaminants Treated*** Diesel fuel and Volatiles, nonhalogenated (BTEX).	***Supplemental Treatment Systems*** Nutrient addition (nitrogen).

Table A-4b. Matrix Characteristics Affecting Treatment Cost or Performance, and Associated Measurement Procedures.
Burlington Northern Railroad Facility, Nebraska: Fueling Pump House.

Parameter	Value	Measurement Procedure
Soil Types	0-35 ft bgs: Fine- to medium-grained silty sands (average 86.1% sand). 35-50 ft bgs: Interbedded sand and silt/clay lenses (average 55.2% sand). 50-75 ft bgs: Fine- to medium-grained silty sand (average 98.8% sand).	Visual description of cuttings. ASTM D422-63 (Laboratory particle size analysis).
Air Permeability	Average of 5 darcys.	Vacuum response tests during air extraction.
pH	Not measured.	EPA Method 9045.
Porosity	Not measured.	None.
Total Organic Carbon	600 mg/kg in one of four samples from uncontaminated soils (other three samples <500 mg/kg).	Not available.
Total Recoverable Petroleum Hydrocarbons (TRPH)	0-35 ft bgs: 4.76 to 133 mg/kg. 35-50 ft bgs: 194 to 89,100 mg/kg. 50-75 ft bgs: <3.33 to 28,500 mg/kg.	EPA Method 418.1.
Non Aqueous Phase Liquids (NAPLs)	None known. Groundwater at approximately 68 to 77 ft bgs.	None.

Table A-4c. Operating Parameters Affecting Treatment Cost or Performance.
Burlington Northern Railroad Facility, Nebraska: Fueling Pump House.

Parameter	Value	Measurement Procedure
Air Flow Rate	Initial air permeability tests: 130-144 scfm. Full-scale operation: 100 scfm.	Not available.
Moisture Content	0-35 ft bgs: 5.9% average. 35-50 ft bgs: 11.1% average. 50-75 ft bgs: 2.1% average.	ASTM D-2216.
Operating Pressure/Vacuum	Not available.	Pressure meter on blower.
Temperature	None measured.	None.
Oxygen Uptake Rate	Initial: 0.004% to 0.009% O_2 per minute. 6-months: 0.002% to 0.005% O_2 / min. 7-months: 0.002% to 0.009% O_2 / min. 1-year: 0.001% to 0.012% O_2 / min. 2-year: 0.001% to 0.015% O_2 / min. 2.5-year: 0.001% to 0.004% O_2 / min.	ISR test methodology in protocol document.
Carbon Dioxide Evolution	Not calculated.	Calculation methodology in protocol document.
Hydrocarbon Degradation Rate	1st 2 yrs: 3,400 mg fuel/kg soil/year (in center of spill). Final (4 yrs of treatment): 130 mg fuel/kg soil/yr.	Calculation methodology in protocol document.
Nutrients and Other Soil Amendments	0-35 ft bgs: 204 mg/kg ammonia-nitrogen; 4 mg/kg nitrate-nitrogen; 4 mg/kg TKN; 177 mg/kg water-soluble phosphate. 35-50 ft bgs: not measured. 50-75 ft bgs: 4.2 mg/kg ammonia-nitrogen; 11 mg/kg nitrate-nitrogen; 4 mg/kg TKN; 6,000 mg/kg water-soluble phosphate.	Not available.

Protocol document: "Test Plan and Technical Protocol for a Field Treatability Test for Bioventing." R.E. Hinchee et al., May 1992.

Table A-4d. Performance Information.
Burlington Northern Railroad Facility, Nebraska: Fueling Pump House.

Performance-Related Topic	Relevant Information
Types of Samples Collected	Soil and soil gas (soil gas used to assess the biodegradation component of contaminant mass removal). Soil gas samples analyzed for TPH and O_2. Soil samples analyzed for TRPH, BTEX, TOC, moisture content and nutrients.
Sampling Frequency and Protocol	Soil samples collected in 1 vent well at 5-foot intervals from surface to 60 feet, and in 6 VMPs at various depths. Periodic monitoring of O_2, CO_2, and TVH (field GC and FID) in soil gas.
Untreated and Treated Contaminant Concentrations	TRPH concentrations with depth (average) and TRPH removal over time are shown in Figure 4-14.
Comparison with Cleanup Goals	Not available.
Analytical Methodology	Identification of methodology not available at this time. No exceptions to standard methodology identified.
QA/QC	Type of QA/QC measures not available at this time. No exceptions to QA/QC protocol or data quality objectives identified.
Other Residuals	Nitrogen addition: gaseous anhydrous ammonia was injected at one VMP, and an aqueous solution of ammonia nitrate fertilizer was added to four other VMPs.

Table A-4e. Site Remediation Project Costs.
Burlington Northern Railroad Facility, Nebraska: Fueling Pump House.

Interagency WBS #	Cost Element	Costs ($)
33-01-XX	Mobilization and Prepatory Work	8,000
33-02-XX	Monitoring, Sampling, Testing, and Analysis - Lab Analysis of Soil Samples (includes drilling costs)	35,000
33-02-XX	Monitoring, Sampling, Testing, and Analysis - Lab Analysis of Soil Gas Samples from Vws and VMPs	44,500
33-03-XX	Site Work	33,000
33-07-XX	Air Pollution / Gas Collection and Control	3,500
33-11-XX	Biological Treatment - Nutrient Addition	7,000
33-19-XX	Disposal (commercial) - Soil Cuttings Disposal	0
33-9X	Other (Reporting and Project Management)	15,000
	Total Costs:	**146,000**

XX = third level WBS cost elements not available.

**Table A-5a. Site Background, Characteristics, and Treatment Systems.
Patrick AFB, Florida: BX Service Station**

Site Background	Site Characteristics	Treatment Systems
Historical Activity that Generated Contamination Automobile fueling station (No SIC Code).	***Media Treated*** Soil.	***Primary Treatment Systems*** Bioventing. Soil Vapor Extraction
Management Practices that Contributed to Contamination Leaking USTs and fuel lines.	***Contaminants Treated*** Gasoline and related nonhalogenated hydrocarbons (BTEX).	***Supplemental Treatment Systems*** Internal combustion engine (SVE off-gas).

**Table A-5b. Matrix Characteristics Affecting Treatment Cost or Performance, and Associated Measurement Procedures.
Patrick AFB, Florida: BX Service Station**

Parameter	Value	Measurement Procedure
Soil Types	Fine- to medium-grained sand.	Visual description of cuttings.
Air Permeability	22 darcys.	Pressure response measurements during air injection (steady-state calculation).
pH	8.7 to 8.8	EPA Method 9045.
Porosity	Not measured (35% estimated).	None.
Total Organic Carbon	Not measured.	None.
Total Petroleum Hydrocarbons (TPH)	11 to 2,730 mg/kg at bioventing test site.	EPA Method 418.1
Non Aqueous Phase Liquids (NAPLs)	None detected.	Oil/water interface probe.

Table A-5c. Operating Parameters Affecting Treatment Cost or Performance. Patrick AFB, Florida: BX Service Station

Parameter	Value	Measurement Procedure
Air Flow Rate	10 scfm.	Not available.
Moisture Content	1.9% to 15% (initial); 6% to 10% (final).	ASTM D-2216.
Operating Pressure/Vacuum	1.0 in. H_2O (pressure) at 6 months.	Direct reading (pressure gauge).
Temperature	88^{o}F (blower) at 6 months.	Direct reading (temperature gauge).
Oxygen Uptake Rate	Initial: 0.0025-0.0028 %/min. 6-mo: 0.0027-0.0045 %/min. 1-yr: 0.0003-0.0006 %/min.	Point (VMP) test. Area-wide test. Point (VMP) test.
Carbon Dioxide Evolution	Not calculated.	Calculation methodology in protocol document.
Hydrocarbon Degradation Rate	Initial: 840 to 970 mg fuel/kg soil/yr. 6-mo: 850 to 1,400 mg fuel/kg soil/yr. 1-yr: 92 to 150 mg fuel/kg soil/yr..	Calculation methodology in protocol document.
Nutrients and Other Soil Amendments	None added.	None.

Protocol document: "Test Plan and Technical Protocol for a Field Treatability Test for Bioventing." R.E. Hinchee et al., May 1992.

Table A-5d. Performance Information. Patrick AFB, Florida: BX Service Station

Performance-Related Topic	Relevant Information
Types of Samples Collected	Soil and soil gas (soil gas used to assess the biodegradation component of contaminant mass removal). Soil gas samples analyzed for TPH, CO_2, and O_2. Soil samples analyzed for TRPH, BTEX, moisture content, grain size, and nutrients.
Sampling Frequency and Protocol	Soil samples were collected from one horizontal VW and two VMP boreholes at depths of 3.5 to 4.5 ft bgs, initially and after 1 year of treatment. Soil gas concentrations of TPH, CO_2, and O_2 were monitored initially and periodically throughout one year of pilot testing.
Untreated and Treated Contaminant Concentrations	TRPH and BTEX concentrations in soil and their removal over time are shown in Figure 4-15.
Comparison with Cleanup Goals	Cleanup goals for site are 50 mg/kg TPH, 1 mg/kg total PAHs, and 0.1 mg/kg BTEX (total). BTEX concentrations were reduced to concentrations below 0.1 mg/kg in 2 of 3 samples; TPH concentrations were reduced to levels below 100 mg/kg (Figure 4-15).
Analytical Methodology	Sampling and pilot testing procedures presented in Protocol Document.
QA/QC	Procedures and requirements presented in a Field Sampling Plan and a Quality Assurance Program Plan for the Bioventing Initiative Project.
Other Residuals	Soil vapor extraction was performed for the first 5 months of treatment and was augmented with off-gas treatment. Air injection was implemented for the final 7 months of initial testing. Full-scale bioventing is now being implemented.

**Table A-5e. Site Remediation Project Costs.
Patrick AFB, Florida: BX Service Station**

Interagency WBS #	Cost Element	Costs ($)
33-01-XX	Mobilization and Prepatory Work	12,300
33-02-XX	Monitoring, Sampling, Testing, and Analysis - Lab Analysis of Soil Samples (includes drilling costs)	35,300
33-02-XX	Monitoring, Sampling, Testing, and Analysis - Lab Analysis of Soil Gas Samples from Vws and VMPs	20,700
33-13-XX	Physical Treatment - Treatment of Off-gas	50,000
33-19-XX	Disposal (commercial) - Soil Cuttings Disposal	0
33-21-XX	Demobilization - Post-Construction Submittals	10,700
33-9X	Other (Proj. mgmt. and regulatory negotiations)	15,000
	Total Costs:	**144,000**

XX = third level WBS cost elements not available.

Table A-6a. Site Background, Characteristics, and Treatment Systems.
Patrick AFB, Florida: FTA-2 Site

Site Background	Site Characteristics	Treatment Systems
Historical Activity that Generated Contamination DOD-Misc. (SIC Code 1711A).	***Media Treated*** Soil.	***Primary Treatment Systems*** Bioventing.
Management Practices that Contributed to Contamination Fire training exercises in an unlined pit. Contaminated fuels and waste oils were burned until 1978; uncontaminated fuels were burned until 1985.	***Contaminants Treated*** Variety of combustible wastes: contaminated and uncontaminated fuels; waste oils.	***Supplemental Treatment Systems*** None.

Table A-6b. Matrix Characteristics Affecting Treatment Cost or Performance, and Associated Measurement Procedures.
Patrick AFB, Florida: FTA-2 Site

Parameter	Value	Measurement Procedure
Soil Types	Unconsolidated fine to medium sand with some clay content down to water table (6 ft bgs).	Visual description of cuttings. ASTM D422-63 (Laboratory particle size analysis).
Air Permeability	32 darcys.	Pressure response measurements during air injection (steady-state calculation).
pH	8.2 to 8.6 (avg. 8.43 from 3 samples)	EPA Method 9045.
Porosity	Not measured (35% estimated).	None.
Total Organic Carbon	Not measured.	None.
Total Petroleum Hydrocarbons (TPH)	3,040 to 13,250 mg/kg at bioventing test site.	EPA Method 418.1
Non Aqueous Phase Liquids (NAPLs)	Not investigated.	None.

**Table A-6c. Operating Parameters Affecting Treatment Cost or Performance.
Patrick AFB, Florida: FTA-2 Site**

Parameter	Value	Measurement Procedure
Air Flow Rate	7.8 scfm (injection) into one horizontal vent well at 6-month testing.	Thermal anemometer.
Moisture Content	3.4% to 4.6% (initial); 5.3% to 12.4% (final).	ASTM D-2216.
Operating Pressure/Vacuum	2.0 in. H_2O (pressure) at 6 months.	Direct reading (pressure gauge).
Temperature	100^{o}F (blower) at 6 months.	Direct reading (temperature gauge).
Oxygen Uptake Rate	Initial: 0.0034-0.0076 %/min. 6-mo: 0.0063-0.0075 %/min. 1-yr: 0.0049-0.0065 %/min.	Point (VMP) test. Area-wide test. Point (VMP) test.
Carbon Dioxide Evolution	Not calculated.	Calculation methodology in protocol document.
Hydrocarbon Degradation Rate	Initial: 1,100 to 2,300 mg fuel/kg soil/yr. 6-mo: 1,500 to 2,000 mg fuel/kg soil/yr. 1-yr: 730 to 1,500 mg fuel/kg soil/yr..	Calculation methodology in protocol document.
Nutrients and Other Soil Amendments	None added.	None.

Protocol document: "Test Plan and Technical Protocol for a Field Treatability Test for Bioventing." R.E. Hinchee et al., May 1992.

**Table A-6d. Performance Information.
Patrick AFB, Florida: FTA-2 Site**

Performance-Related Topic	Relevant Information
Types of Samples Collected	Soil and soil gas (soil gas used to assess the biodegradation component of contaminant mass removal). Soil gas samples analyzed for TPH, CO_2, and O_2. Soil samples analyzed for TRPH, BTEX, moisture content, grain size, and nutrients.
Sampling Frequency and Protocol	Soil samples were collected from one horizontal VW and two VMP boreholes at depths of 3.5 to 4 ft bgs, initially and after 1 year of treatment. Soil gas concentrations of TPH, CO_2, and O_2 were monitored initially and periodically throughout one year of pilot testing.
Untreated and Treated Contaminant Concentrations	TRPH and BTEX concentrations in soil and their removal over time are shown in Figure 4-16.
Comparison with Cleanup Goals	No specific cleanup goals have been set for this site..
Analytical Methodology	Sampling and pilot testing procedures presented in Protocol Document.
QA/QC	Procedures and requirements presented in a Field Sampling Plan and a Quality Assurance Program Plan for the Bioventing Initiative Project.
Other Residuals	None.

Table A-6e. Site Remediation Project Costs.
Patrick AFB, Florida: FTA-2 Site

Interagency WBS #	Cost Element	Costs ($)
33-01-XX	Mobilization and Prepatory Work	6,000
33-02-XX	Monitoring, Sampling, Testing, and Analysis - Lab Analysis of Soil Samples (includes drilling costs)	4,000
33-02-XX	Monitoring, Sampling, Testing, and Analysis - Lab Analysis of Soil Gas Samples from Vws and VMPs	5,500
33-03-XX	Site Work	10,000
33-21-XX	Demobilization - Post-Construction Submittals	6,500
33-9X	Other (Proj. mgmt. and regulatory negotiations)	5,000
	Total Costs:	**37,000**

XX = third level WBS cost elements not available.

Table A-7a. Site Background, Characteristics, and Treatment Systems.
Offutt AFB, Nebraska: Building 406 Site

Site Background	Site Characteristics	Treatment Systems
Historical Activity that Generated Contamination Air Transportation, Nonscheduled. (SIC Code 4522).	***Media Treated*** Soil.	***Primary Treatment Systems*** Bioventing.
Management Practices that Contributed to Contamination Six Underground Storage Tanks, each 50,000 gallon capacity, at a pumphouse facility. Historical leaks, quantities, and dates unknown.	***Contaminants Treated*** JP-4 Jet Fuel.	***Supplemental Treatment Systems*** None.

Table A-7b. Matrix Characteristics Affecting Treatment Cost or Performance, and Associated Measurement Procedures.
Offutt AFB, Nebraska: Building 406 Site

Parameter	Value	Measurement Procedure
Soil Types	Silt with some clay and sand. UST excavation backfill of unconsolidated silts and other materials.	Visual description of cuttings. ASTM D422-63 (Laboratory particle size analysis).
Air Permeability	3.6 darcys.	Pressure response measurements during air injection (steady-state calculation).
pH	7.4 to 8.2	EPA Method 9045.
Porosity	Not measured (45% estimated).	None.
Total Organic Carbon	Not measured.	None.
Total Petroleum Hydrocarbons (TPH)	<6.5 to 11,700 mg/kg at bioventing test site.	EPA Method 418.1
Non Aqueous Phase Liquids (NAPLs)	Not investigated.	None.

Table A-7c. Operating Parameters Affecting Treatment Cost or Performance.
Offutt AFB, Nebraska: Building 406 Site

Parameter	Value	Measurement Procedure
Air Flow Rate	2.7 scfm (injection) into each of 4 vent wells.	Pitot tube.
Moisture Content	22.5% avg (initial); 20.0% avg (1-yr); 20.1 % avg (2-yr).	ASTM D-2216.
Operating Pressure/Vacuum	2.7 in. H_2O (pressure) initially and at 1 yr.	Direct reading (pressure gauge).
Temperature	95°F (blower) initially and 124 °F at 1 yr.	Direct reading (temperature gauge).
Oxygen Uptake Rate	Initial: 0.0066-0.17 %/min. (0.094 avg) 6-mo: 0.0036-0.0092 %/min. (0.0055 avg) 1-yr: 0.0020-0.0059 %/min. (0.0044 avg) 18-mo: 0.0016-0.0046 %/min. (0.0027 avg) 2-yr: 0.0012-0.025 %/min. (0.011 avg)	Point (VMP) test. Area-wide test. Point (VMP) test. Area-wide test. Point (VMP) test.
Carbon Dioxide Evolution	Not calculated.	Calculation methodology in protocol document.
Hydrocarbon Degradation Rate	Initial: 1,000 to 24,000 mg fuel/kg soil/yr. (13,700 avg) 6-mo: 630 to 1,500 mg fuel/kg soil/yr. (1,000 avg) 1-yr: 350 to 2,200 mg fuel/kg soil/yr. (1,200 avg) 18-mo: 230 to 1,000 mg fuel/kg soil/yr. (510 avg) 2-yr: 160 to 3,300 mg fuel/kg soil/yr. (1,400 avg)	Calculation methodology in protocol document.
Nutrients and Other Soil Amendments	None added.	None.

Protocol document: "Test Plan and Technical Protocol for a Field Treatability Test for Bioventing." R.E. Hinchee et al., May 1992.

Table A-7d. Performance Information.
Offutt AFB, Nebraska: Building 406 Site

Performance-Related Topic	Relevant Information
Types of Samples Collected	Soil and soil gas (soil gas used to assess the biodegradation component of contaminant mass removal). Soil gas samples analyzed for TPH, CO_2, and O_2. Soil samples analyzed for TRPH, BTEX, moisture content, grain size, and nutrients.
Sampling Frequency and Protocol	12 soil samples were collected initially and 16 soil samples were collected after 1 and 2 years of treatment. Soil gas concentrations of TPH, CO_2, and O_2 were monitored initially and periodically throughout one year of pilot testing.
Untreated and Treated Contaminant Concentrations	TRPH and BTEX concentrations in soil and their removal over time are shown in Figure 4-17.
Comparison with Cleanup Goals	No specific cleanup goals have been set for this site.
Analytical Methodology	Sampling and pilot testing procedures presented in Protocol Document.
QA/QC	Procedures and requirements presented in a Field Sampling Plan and a Quality Assurance Program Plan for the Bioventing Initiative Project.
Other Residuals	None.

Table A-7e. Site Remediation Project Costs.
Offutt AFB, Nebraska: Building 406 Site

Interagency WBS #	Cost Element	Costs ($)
33-01-XX	Mobilization and Prepatory Work	12,500
33-02-XX	Monitoring, Sampling, Testing, and Analysis - Lab Analysis of Soil Samples (includes drilling costs)	17,400
33-02-XX	Monitoring, Sampling, Testing, and Analysis - Lab Analysis of Soil Gas Samples from Vws and VMPs	14,500
33-03-XX	Site Work	20,200
33-21-XX	Demobilization - Post-Construction Submittals	12,400
33-9X	Other (Proj. mgmt. and regulatory negotiations)	9,000
	Total Costs:	**86,000**

XX = third level WBS cost elements not available.

Table A-8a. Site Background, Characteristics, and Treatment Systems.
Hickam AFB, Hawaii: Area H

Site Background	Site Characteristics	Treatment Systems
Historical Activity that Generated Contamination Transportation, Refined Petroleum Pipelines. (SIC Code 4613).	***Media Treated*** Soil.	***Primary Treatment Systems*** Bioventing.
Management Practices that Contributed to Contamination Long-term leaks from several pipelines; dates and quantities unknown. Site represents one portion of total fuel-contaminated area which covers 40 acres of facility.	***Contaminants Treated*** Aviation Fuel (extensive fuel free product on water table).	***Supplemental Treatment Systems*** Bioslurping pilot test for free-product removal.

Table A-8b. Matrix Characteristics Affecting Treatment Cost or Performance, and Associated Measurement Procedures.
Hickam AFB, Hawaii: Area H

Parameter	Value	Measurement Procedure
Soil Types	Clay, sand, and coralline rubblestone underlain by volcanic tuff.	Visual description of cuttings. ASTM D422-63 (Laboratory particle size analysis).
Air Permeability	Not calculated. Matrix of volcanic tuff in vadose zone is relatively impermeable (but injected air is able to move through fractures or other pathways)	Pressure response measurements during air injection (steady-state calculation).
pH	8.9 to 9.0	EPA Method 9045.
Porosity	Not measured (40% estimated).	None.
Total Organic Carbon	Not measured.	None.
Total Petroleum Hydrocarbons (TPH) Total BTEX	<5 to 23.9 mg/kg at bioventing test site. 5.8 to 33.3 mg/kg at bioventing test site.	EPA Method 418.1 EPA Method 8020
Non Aqueous Phase Liquids (NAPLs)	Investigations in 1985 detected >6 ft apparent thickness of free product.	Not reported.

Table A-8c. Operating Parameters Affecting Treatment Cost or Performance.
Hickam AFB, Hawaii: Area H

Parameter	Value	Measurement Procedure
Air Flow Rate	19 scfm (injection) into 1 vent well.	Estimated from blower curve when injecting 100% blower air.
Moisture Content	24.6% avg (initial); 24.1% avg (1-yr).	ASTM D-2216.
Operating Pressure/Vacuum	2.4 psi (pressure) at 6 mo.	Direct reading (pressure gauge).
Temperature	104^{o}F (blower) at 6 mo.	Direct reading (temperature gauge).
Oxygen Uptake Rate	Initial: 0.0043-0.02 %/min. 6-mo: 0.000064-0.0052 %/min. 1-yr: 0.000031-0.0003 %/min.	Point (VMP) test. Area-wide test. Point (VMP) test.
Carbon Dioxide Evolution	Not calculated.	Calculation methodology in protocol document.
Hydrocarbon Degradation Rate	Initial: <10 to 210 mg fuel/kg soil/yr. 6-mo: <10 to 120 mg fuel/kg soil/yr. 1-yr: <10 to 120 mg fuel/kg soil/yr.	Calculation methodology in protocol document.
Nutrients and Other Soil Amendments	None added.	None.

Protocol document: "Test Plan and Technical Protocol for a Field Treatability Test for Bioventing." R.E. Hinchee et al., May 1992.

Table A-8d. Performance Information.
Hickam AFB, Hawaii: Area H

Performance-Related Topic	Relevant Information
Types of Samples Collected	Soil and soil gas (soil gas used to assess the biodegradation component of contaminant mass removal). Soil gas samples analyzed for TPH, CO_2, and O_2. Soil samples analyzed for TRPH, BTEX, moisture content, grain size, and nutrients.
Sampling Frequency and Protocol	Soil samples at 18 ft bgs were collected from 3 locations initially and after 1 year of treatment. Soil gas concentrations of TPH, CO_2, and O_2 were monitored initially and periodically throughout one year of pilot testing.
Untreated and Treated Contaminant Concentrations	TRPH and BTEX concentrations in soil and their removal over time are shown in Figure 4-18.
Comparison with Cleanup Goals	Preliminary Remediation Goals (PRGs) were developed from recommended cleanup criteria presented in State of Hawaii Department of Health guidance. PRGs were 0.05 mg/kg benzene, 7.0 mg/kg toluene, 10.0 mg/kg ethylbenzene, and 100 mg/kg total xylenes.
Analytical Methodology	Sampling and pilot testing procedures presented in Protocol Document.
QA/QC	Procedures and requirements presented in a Field Sampling Plan and a Quality Assurance Program Plan for the Bioventing Initiative Project.
Other Residuals	None.

Guidance document: "Technical Guidance Manual for Underground Storage Tank Closure and Release Response." State of Hawaii, Department of Health, 1992.

Table A-8e. Site Remediation Project Costs.
Hickam AFB, Hawaii: Area H

Interagency WBS #	Cost Element	Costs ($)
33-01-XX	Mobilization and Prepatory Work	5,500
33-02-XX	Monitoring, Sampling, Testing, and Analysis - Lab Analysis of Soil Samples (includes drilling costs)	12,000
33-02-XX	Monitoring, Sampling, Testing, and Analysis - Lab Analysis of Soil Gas Samples from Vws and VMPs	8,500
33-03-XX	Site Work	10,000
33-21-XX	Demobilization - Post-Construction Submittals	5,000
33-9X	Other (Proj. mgmt. and regulatory negotiations)	5,000
	Total Costs:	**46,000**

XX = third level WBS cost elements not available.

Table A-9a. Site Background, Characteristics, and Treatment Systems.
Hickam AFB, Hawaii: Area K

Site Background	Site Characteristics	Treatment Systems
Historical Activity that Generated Contamination Transportation, Refined Petroleum Pipelines. (SIC Code 4613).	***Media Treated*** Soil.	***Primary Treatment Systems*** Bioventing.
Management Practices that Contributed to Contamination Long-term leaks from a JP-4 jet fuel pipeline; dates and quantities unknown.	***Contaminants Treated*** JP-4 Jet Fuel (extensive fuel free product on water table).	***Supplemental Treatment Systems*** Previous work at site included ineffective skimming for free-product removal.

Table A-9b. Matrix Characteristics Affecting Treatment Cost or Performance, and Associated Measurement Procedures.
Hickam AFB, Hawaii: Area K

Parameter	Value	Measurement Procedure
Soil Types	Coralline rubblestone and coral sand from surface to 5 ft bgs underlain by coralline rubblestone and clay (clay content increases with depth).	Visual description of cuttings. ASTM D422-63 (Laboratory particle size analysis).
Air Permeability	5.27 darcys.	Pressure response measurements during air injection (steady-state calculation).
pH	8.1 to 8.5	EPA Method 9045.
Porosity	Not measured (40% estimated).	None.
Total Organic Carbon	Not measured.	None.
Total Petroleum Hydrocarbons (TPH) Total BTEX	<5 to 69 mg/kg at bioventing test site. 22.0 to 78.2 mg/kg at bioventing test site.	EPA Method 418.1 EPA Method 8020
Non Aqueous Phase Liquids (NAPLs)	Investigations in 1985 detected up to 1 ft apparent thickness of free product.	Not reported.

Table A-9c. Operating Parameters Affecting Treatment Cost or Performance.
Hickam AFB, Hawaii: Area K

Parameter	Value	Measurement Procedure
Air Flow Rate	20 acfm (injection) into 1 vent well.	Estimated from blower curve when injecting 100% blower air.
Moisture Content	14.0% avg (initial); 13.7% avg (1-yr).	ASTM D-2216.
Operating Pressure/Vacuum	28 in H_2O (pressure) at 6 mo.	Direct reading (pressure gauge).
Temperature	130^oF (blower) at 6 mo.	Direct reading (temperature gauge).
Oxygen Uptake Rate	Initial: 0.013-0.026 %/min. 6-mo: 0.0062-0.0092 %/min. 1-yr: 0.0057-0.0072 %/min.	Point (VMP) test. Area-wide test. Point (VMP) test.
Carbon Dioxide Evolution	Not calculated.	Calculation methodology in protocol document.
Hydrocarbon Degradation Rate	Initial: 1,800 to 5,000 mg fuel/kg soil/yr. 6-mo: 1,100 to 1,600 mg fuel/kg soil/yr. 1-yr: 1,100 to 1,400 mg fuel/kg soil/yr.	Calculation methodology in protocol document.
Nutrients and Other Soil Amendments	None added.	None.

Protocol document: "Test Plan and Technical Protocol for a Field Treatability Test for Bioventing." R.E. Hinchee et al., May 1992.

Table A-9d. Performance Information.
Hickam AFB, Hawaii: Area K

Performance-Related Topic	Relevant Information
Types of Samples Collected	Soil and soil gas (soil gas used to assess the biodegradation component of contaminant mass removal). Soil gas samples analyzed for TPH, CO_2, and O_2. Soil samples analyzed for TRPH, BTEX, moisture content, grain size, and nutrients.
Sampling Frequency and Protocol	Soil samples at 5.5-6.5 ft bgs were collected from 3 locations initially and after 1 year of treatment. Soil gas concentrations of TPH, CO_2, and O_2 were monitored initially and periodically throughout one year of pilot testing.
Untreated and Treated Contaminant Concentrations	TRPH and BTEX concentrations in soil and their removal over time are shown in Figure 4-19.
Comparison with Cleanup Goals	Preliminary Remediation Goals (PRGs) were developed from recommended cleanup criteria presented in State of Hawaii Department of Health guidance. PRGs were 0.05 mg/kg benzene, 7.0 mg/kg toluene, 10.0 mg/kg ethylbenzene, and 100 mg/kg total xylenes.
Analytical Methodology	Sampling and pilot testing procedures presented in Protocol Document.
QA/QC	Procedures and requirements presented in a Field Sampling Plan and a Quality Assurance Program Plan for the Bioventing Initiative Project.
Other Residuals	None.

Guidance document: "ìTechnical Guidance Manual for Underground Storage Tank Closure and Release Response." State of Hawaii, Department of Health, 1992.

Table A-9e. Site Remediation Project Costs.
Hickam AFB, Hawaii: Area K

Interagency WBS #	Cost Element	Costs ($)
33-01-XX	Mobilization and Prepatory Work	5,500
33-02-XX	Monitoring, Sampling, Testing, and Analysis - Lab Analysis of Soil Samples (includes drilling costs)	8,100
33-02-XX	Monitoring, Sampling, Testing, and Analysis - Lab Analysis of Soil Gas Samples from Vws and VMPs	7,000
33-03-XX	Site Work	8,400
33-21-XX	Demobilization - Post-Construction Submittals	4,200
33-9X	Other (Proj. mgmt. and regulatory negotiations)	4,300
	Total Costs:	**37,500**

XX = third level WBS cost elements not available.

Table A-10a. Site Background, Characteristics, and Treatment Systems.
Hickam AFB, Hawaii: Site 2

Site Background	Site Characteristics	Treatment Systems
Historical Activity that Generated Contamination DOD-Misc. (SIC Code 1711A).	***Media Treated*** Soil.	***Primary Treatment Systems*** Bioventing.
Management Practices that Contributed to Contamination Open-bottomed Disposal Pit (approximately 20 feet deep) was use for disposal of waste petroleum products.	***Contaminants Treated*** Petroleum hydrocarbons.	***Supplemental Treatment Systems*** None. (Soil vapor extraction pilot testing with treatment of off-gas by internal combustion engine is proposed for 1997).

Table A-10b. Matrix Characteristics Affecting Treatment Cost or Performance, and Associated Measurement Procedures.
Hickam AFB, Hawaii: Site 2

Parameter	Value	Measurement Procedure
Soil Types	Unconsolidated clay and silt (0-25 ft bgs) overlying saprolite (25-110 ft bgs). Weathered, fractured basalt exists below the saprolite.	Visual description of cuttings. ASTM D422-63 (Laboratory particle size analysis).
Air Permeability	4.15 darcys.	Pressure response measurements during air injection (steady-state calculation).
pH	4.0 to 5.9	EPA Method 9045.
Porosity	Not measured (50% estimated).	None.
Total Organic Carbon	Not measured.	None.
Total Petroleum Hydrocarbons (TPH)	<7.5 to 3,600 mg/kg at bioventing test site.	EPA Method 418.1
Non Aqueous Phase Liquids (NAPLs)	Not investigated.	None.

Table A-10c. Operating Parameters Affecting Treatment Cost or Performance.
Hickam AFB, Hawaii: Site 2

Parameter	Value	Measurement Procedure
Air Flow Rate	75 acfm (injection) into 1 vent well.	Estimated from blower curve when injecting 100% blower air.
Moisture Content	33.7% avg (initial); 30.6% avg (1-yr).	ASTM D-2216.
Operating Pressure/Vacuum	55 in H_2O (pressure) initially. 19 in H_2O (pressure) after 6 months.	Direct reading (pressure gauge).
Temperature	114^{o}F (blower) after 6 months.	Direct reading (temperature gauge).
Oxygen Uptake Rate	Initial: 0.0010-0.018 %/min. 6-mo: 0.00018-0.013 %/min. 1-yr: 0.0018-0.020 %/min.	Point (VMP) test. Area-wide test. Point (VMP) test.
Carbon Dioxide Evolution	Not calculated.	Calculation methodology in protocol document.
Hydrocarbon Degradation Rate	Initial: <10 to 1,130 mg fuel/kg soil/yr. 6-mo: <10 to 1,600 mg fuel/kg soil/yr. 1-yr: 100 to 2,300 mg fuel/kg soil/yr.	Calculation methodology in protocol document.
Nutrients and Other Soil Amendments	None added.	None.

Protocol document: "Test Plan and Technical Protocol for a Field Treatability Test for Bioventing." R.E. Hinchee et al., May 1992.

Table A-10d. Performance Information.
Hickam AFB, Hawaii: Site 2

Performance-Related Topic	Relevant Information
Types of Samples Collected	Soil and soil gas (soil gas used to assess the biodegradation component of contaminant mass removal). Soil gas samples analyzed for TPH, CO_2, and O_2. Soil samples analyzed for TRPH, BTEX, moisture content, grain size, and nutrients. Initial soil samples from vent well borehole also analyzed for halogenated VOCs and semi-volatile organics.
Sampling Frequency and Protocol	Soil samples between 30 and 60 ft bgs were collected from 3 locations initially and after 1 year of treatment. Soil gas concentrations of TPH, CO_2, and O_2 were monitored initially and periodically throughout one year of pilot testing.
Untreated and Treated Contaminant Concentrations	TRPH and BTEX concentrations in soil and their removal over time are shown in Figure 4-20.
Comparison with Cleanup Goals	Preliminary Remediation Goals (PRGs) were developed from recommended cleanup criteria presented in State of Hawaii Department of Health guidance. PRGs were 0.05 mg/kg benzene, 7.0 mg/kg toluene, 10.0 mg/kg ethylbenzene, and 100 mg/kg total xylenes.
Analytical Methodology	Sampling and pilot testing procedures presented in Protocol Document.
QA/QC	Procedures and requirements presented in a Field Sampling Plan and a Quality Assurance Program Plan for the Bioventing Initiative Project.
Other Residuals	None.

Guidance document: "Technical Guidance Manual for Underground Storage Tank Closure and Release Response." State of Hawaii, Department of Health, 1992.

Table A-10e. Site Remediation Project Costs.
Hickam AFB, Hawaii: Site 2

Interagency WBS #	Cost Element	Costs ($)
33-01-XX	Mobilization and Prepatory Work	5,500
33-02-XX	Monitoring, Sampling, Testing, and Analysis - Lab Analysis of Soil Samples (includes drilling costs)	60,000
33-02-XX	Monitoring, Sampling, Testing, and Analysis - Lab Analysis of Soil Gas Samples from Vws and VMPs	8,500
33-03-XX	Site Work	10,300
33-21-XX	Demobilization - Post-Construction Submittals	7,500
33-9X	Other (Proj. mgmt. and regulatory negotiations)	6,700
	Total Costs:	**98,500**

XX = third level WBS cost elements not available.

Table A-11a. Site Background, Characteristics, and Treatment Systems.
US Coast Guard Support Center, Kodiak, Alaska: Site 6B-Fuel Farm (Tank 191)

Site Background	Site Characteristics	Treatment Systems
Historical Activity that Generated Contamination Air Transportation, Nonscheduled. (SIC Code 4522).	***Media Treated*** Soil.	***Primary Treatment Systems*** Bioventing.
Management Practices that Contributed to Contamination 13 large Underground Storage Tanks and Aboveground Storage Tanks. Tank 191 is inactive 567,000 gallon capacity UST. Leaks from this tank were reported to be 500 to 2,300 gallons per day in the mid 1950s.	***Contaminants Treated*** Diesel fuel and JP-5 jet fuel.	***Supplemental Treatment Systems*** None.

Table A-11b. Matrix Characteristics Affecting Treatment Cost or Performance, and Associated Measurement Procedures.
US Coast Guard Support Center, Kodiak, Alaska: Site 6B-Fuel Farm (Tank 191)

Parameter	Value	Measurement Procedure
Soil Types	Gravel and sand fill overlaying weathered slate bedrock. USTs placed within bedrock excavations.	Visual description of cuttings. ASTM D422-63 (Laboratory particle size analysis).
Air Permeability	154 darcys.	Pressure response measurements during air injection (steady-state calculation).
pH	6.6 to 7.7	EPA Method 9045.
Porosity	Not measured (30% estimated).	None.
Total Organic Carbon	Not measured.	None.
Total Petroleum Hydrocarbons (TPH)	10 to 1,200 mg/kg (TEPH) <5.0 to 11 mg/kg TVPH at bioventing test site. Up to 3,400 mg/kg TEPH sitewide.	EPA Method 8015 (diesel) EPA Method 8015 (gasoline) EPA Method 418.1
Non Aqueous Phase Liquids (NAPLs)	Not detected.	Oil-water interface probe.

Table A-11c. Operating Parameters Affecting Treatment Cost or Performance.
US Coast Guard Support Center, Kodiak, Alaska: Site 6B-Fuel Farm (Tank 191)

Parameter	Value	Measurement Procedure
Air Flow Rate	26 scfm (injection) into one vent well.	Thermal anemometer.
Moisture Content	9.2% avg (initial); 24.5% avg (1-yr).	ASTM D-2216.
Operating Pressure/Vacuum	2.5 in. H_2O (pressure) initially, and 3.5 in. H_2O at 6 months.	Direct reading (pressure gauge).
Temperature	112^{o}F (blower) initially and 110 ^{o}F at 6 months.	Direct reading (temperature gauge).
Oxygen Uptake Rate	Initial: 0.0084-0.037 %/min. 6-mo: 0.013-0.0042 %/min. 1-yr: 0.0013-0.0055 %/min.	Point (VMP) test. Area-wide test. Point (VMP) test.
Carbon Dioxide Evolution	Not calculated.	Calculation methodology in protocol document.
Hydrocarbon Degradation Rate	Initial: 1,200 to 5,200 mg fuel/kg soil/yr. 6-mo: 180 to 550 mg fuel/kg soil/yr. 1-yr: 170 to 830 mg fuel/kg soil/yr.	Calculation methodology in protocol document.
Nutrients and Other Soil Amendments	None added.	None.

Protocol document: "Test Plan and Technical Protocol for a Field Treatability Test for Bioventing." R.E. Hinchee et al., May 1992.

Table A-11d. Performance Information.
US Coast Guard Support Center, Kodiak, Alaska: Site 6B-Fuel Farm (Tank 191)

Performance-Related Topic	Relevant Information
Types of Samples Collected	Soil and soil gas (soil gas used to assess the biodegradation component of contaminant mass removal). Soil gas samples analyzed for TPH, CO_2, and O_2. Soil samples analyzed for TEPH, TVPH, BTEX, moisture content, grain size, and nutrients.
Sampling Frequency and Protocol	Soil samples at 10 ft bgs from 3 locations were collected initially and after 1 year of treatment. Soil gas concentrations of TPH, CO_2, and O_2 were monitored initially and periodically throughout one year of pilot testing.
Untreated and Treated Contaminant Concentrations	TEPH, TVPH, and BTEX concentrations in soil and their removal over time are shown in Figure 4-21.
Comparison with Cleanup Goals	No specific cleanup goals have been set for this site.
Analytical Methodology	Sampling and pilot testing procedures presented in Protocol Document.
QA/QC	Procedures and requirements presented in a Field Sampling Plan and a Quality Assurance Program Plan for the Bioventing Initiative Project.
Other Residuals	None.

Table A-11e. Site Remediation Project Costs.
US Coast Guard Support Center, Kodiak, Alaska: Site 6B-Fuel Farm (Tank 191)

Interagency WBS #	Cost Element	Costs ($)
33-01-XX	Mobilization and Prepatory Work	11,300
33-02-XX	Monitoring, Sampling, Testing, and Analysis - Lab Analysis of Soil Samples (includes drilling costs)	12,200
33-02-XX	Monitoring, Sampling, Testing, and Analysis - Lab Analysis of Soil Gas Samples from Vws and VMPs	11,100
33-03-XX	Site Work	17,500
33-21-XX	Demobilization - Post-Construction Submittals	9,700
33-9X	Other (Proj. mgmt. and regulatory negotiations)	7,200
	Total Costs:	**69,000**

XX = third level WBS cost elements not available.