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Manual

Bioventing Principles and Practice

Volume II: Bioventing Design

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Manual

Principles and Practices of Bioventing
Volume II: Bioventing Design

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Notice

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List of Symbols and Acronyms

AFB	Air Force Base
AFCEE	U.S. Air Force Center for Environmental Excellence
AL/EQ	Armstrong Laboratory Environics Directorate
AOC	area of concentration
BTEX	benzene, toluene, ethylbenzene, and xylenes
cfm	cubic feet per minute
CPT	cone penetrometer
DNAPL	dense nonaqueous phase liquid
EPA	U.S. Environmental Protection Agency
FID	flame ionization detector
GAC	granular activated carbon
ICE	internal combustion engine
LEL	lower explosive limit
LNAPL	less dense nonaqueous phase liquid
MP	monitoring point
MW	monitoring well
NAS	Naval Air Station
NFPA	National Fire Protection Association
NPT	national pipe thread
PAH	polycyclic aromatic hydrocarbon
PCB	polychlorinated biphenyl
PID	photoionization detector
PVC	polyvinyl chloride
RD&A	research, development, and acquisition
scfm	standard cubic feet per minute
SGS	soil gas survey
SVE	soil vacuum extraction
TCE	trichloroethylene
TKN	total Kjeldahl nitrogen
TPH	total petroleum hydrocarbon
UCL	upper confidence limit
UST	underground storage tank
VOC	volatile organic carbon

C_S	quantity sorbed to the solid matrix (g_x/g_{soil})
C_V	volumetric concentration in the vapor phase (g_x/L_{vapor})
C_{vsat}	saturated vapor concentration (g_x/L_{vapor})
C_W	volumetric concentration in the aqueous phase ($g_x/L_{aqueous}$)
E_a	activation energy (cal/mole)
f_{oc}	organic carbon fraction
k	maximum rate of substrate utilization (g_S/g_X-min)
k_B	biodegradation rate (mg hydrocarbon/ kg soil-day)
k_d	endogenous respiration rate (day^{-1})
K_d	sorption coefficient ($L_{aqueous}/g_{soil}$)
k_o	baseline biodegradation rate (% O_2/day)
K_{ow}	octanol/water partition coefficient
K_S	Monod half-velocity constant (g_S/L)
k_T	temperature-corrected biodegradation rate (% O_2/day)
MW	molecular weight ($g_x/mole_x$)
P_V	vapor pressure of pure contaminant at temperature T (atm)
R	gas constant (1.987 cal/°K-mol)
R	gas constant (L-atm/mole-°K)
R_I	radius of influence
S	concentration of the primary substrate (contaminant) (g_S/L)
s_x	solubility in water (g_x/L_{water})
t	time (minutes)
T_{abs}	absolute temperature (°K)
χ	mole fraction (dimensionless)
X	concentration of microorganisms (g_X/L)
Y	cell yield (mg biomass/mg hydrocarbon)

Conversion Factors

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

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

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

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

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

Chapter 1
Site Characterization

Site characterization is an important step in determining the feasibility of bioventing and in providing information for a full-scale bioventing design. Chapter 1 discusses site characterization methods that are recommended for bioventing sites based on field experience and a statistical analysis of Bioventing Initiative data. These parameters have proven to be the most useful in predicting the potential applicability of bioventing at a contaminated site. Figure 1-1 summarizes the sequence of events for site characterization of a typical site. Each step presented in Figure 1-1 is discussed in the following sections.

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

- Review of existing site data (Section 1.1).
- Soil gas survey (Section 1.2).
- Soil characterization (Section 1.3).
- In situ respiration testing (Section 1.4).
- Soil gas permeability testing, and radius of influence (Section 1.5).

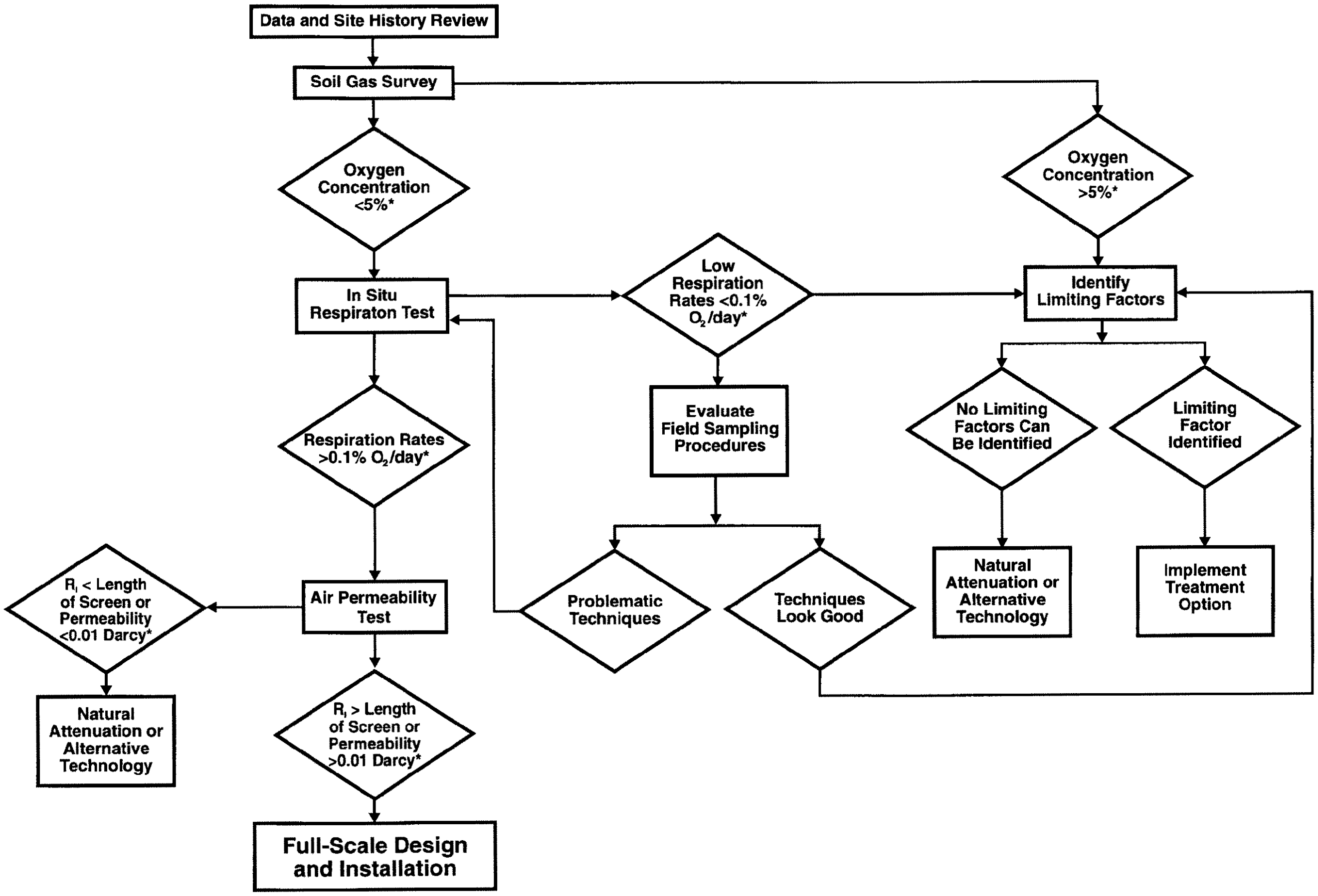

Figure 1-1. Conceptual decision tree for determining the potential applicability of bioventing at a contaminated site.

1.1 Existing Data and Site History Review

The first step in designing and installing a bioventing system is to review the existing site data. An initial review of site data provides preliminary information for determining whether bioventing is a feasible option for a specific site. Also, the initial data review helps to identify any additional information that is needed to complete the bioventing design.

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

- Types of contaminants.
- Quantity and distribution of free product (if present).
- Historical water table levels.
- Three-dimensional distribution of contaminant.
- Potential for a continuing source of contamination because of leaking pipes or tanks.
- Particle size distribution or soil gas permeability.
- Surface features such as concrete or asphalt.

At this stage, the most important information is type of contaminant. Bioventing is applicable only to compounds that are biodegraded aerobically, such as petroleum hydrocarbons.[1] Compounds such as chlorinated solvents tend to degrade more readily under anaerobic conditions. In most cases, the contaminant is petroleum hydrocarbons; however, bioventing also may potentially be applied at some sites contaminated with both chlorinated solvents and petroleum hydrocarbons.

If significant free product is present, removal must be addressed either before or simultaneously with bioventing. Bioventing alone is not sufficient to remediate sites with large quantities of free product. Bioslurping technology combines bioventing and free product removal and is currently under development by the Air Force (Kittel et al., 1995).

Historical water table levels also are important to determine whether contamination is available for bioventing or is present below the water table. If significant contamination is present below the water table, dewatering may be needed to complete site remediation. At some sites, bioventing may be feasible only during periods of seasonal low water tables.

The three-dimensional distribution of the contaminant provides information necessary for generating an initial estimate of the screen depths and the size of the bioventing system that will be required. This initial estimate provides a guideline for conducting the soil gas survey and for collecting initial soil samples necessary to estimate the initial mass of contamination at the site.

The potential for a continuing source of contamination must be addressed at every site. Often, contaminated sites are created from leaking underground pipes or tanks. These sources must be eliminated for bioventing to achieve cleanup.

If available, data on particle size distribution or permeability are useful for determining the potential for applying bioventing. Because the success of bioventing depends on the ability to move air through the soil, particle size or permeability measurements are crucial parameters. Unless these values are extreme (saturated clay), however, initial treatability studies should be conducted to determine bioventing applicability.

If surface features such as concrete or asphalt are present, excavation methods would be too disruptive, so bioventing is the only cost-effective treatment option available. If contamination is present beneath buildings, the bioventing system must be designed to ensure that contaminants do not rise up into the buildings.

Example 1-1. Review of Existing Data and Site History: Bioventing is being considered at area of concern (AOC) A at Keesler Air Force Base (AFB), Mississippi, and the following information is known:

- The soil was contaminated from leaking underground gasoline storage tanks.
- Storage tanks were removed in 1991.
- A site map (Figure 1-2) was provided with limited total petroleum hydrocarbon (TPH) soil sample results.
- The soils are very sandy.

After examining the existing site data, the following conclusions are made:

- The type of contaminant is gasoline, a very good candidate for bioventing. Based on this information, a soil gas survey is scheduled.
- No information was provided on free product or on water levels. Given that ground-water monitoring wells are shown in Figure 1-2, some information probably exists. Although further attempts will be made to find the additional information, collection of free product and water level measurements will also take place during the soil gas survey phase.
- The quantity of the release is unknown because contamination occurred over a long period; however, the limited soil sampling provides a general guideline for the area in which to conduct a soil gas survey.
- The storage tanks were removed, so a continuing source of contamination is not a factor.

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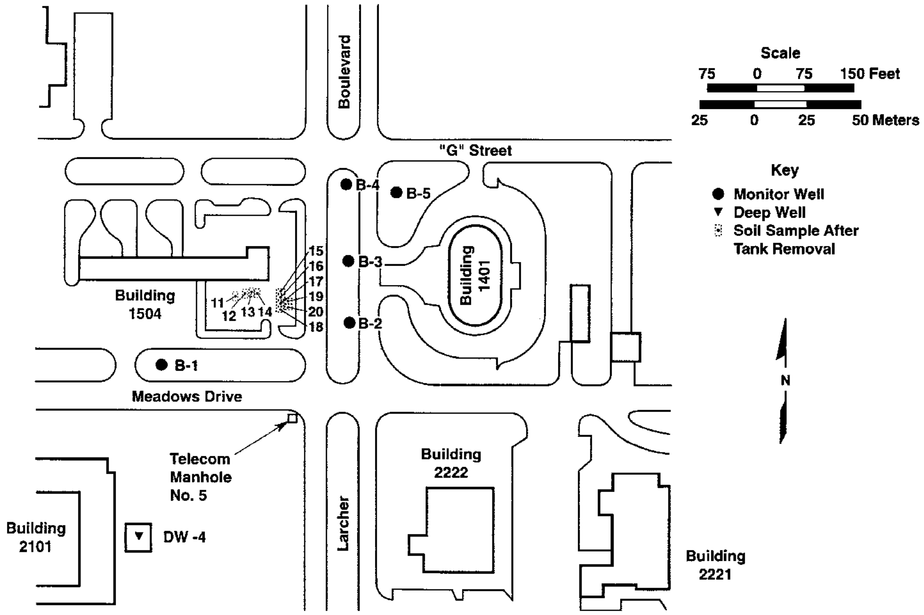
[1] See Volume I for a discussion of compounds degraded through bioventing.



Sample ID

TPH (mg/kg)	11	12	13	14	15	16	17	18	19	20	West	North	East	South
	–	85.6	77.6	–	1030	1010	540	–	741	814	–	1850	1640	758

Figure 1-2. Site map showing well locations and TPH soil concentrations at AOC A, Keesler AFB, Mississippi.

- Particle size distribution was known; soils are sandy, making this site an excellent candidate for bioventing.

1.2 Soil Gas Survey

At sites where the contamination is at sufficiently shallow depths (typically less than 20 ft [6.1 m]), a soil gas survey should be conducted initially to determine whether oxygen-limited conditions exist. Oxygen-limited conditions are a good indicator of whether bacteria are present that are capable of degrading the contaminants of concern because soil gas in uncontaminated vadose zone soils generally exhibits oxygen concentrations equivalent to ambient air. The soil gas survey also assists in delineating the extent of contamination and locating suitable areas for vent well and monitoring point placement. Data on soil gas concentrations of oxygen, carbon dioxide, and TPH can provide valuable insight into the extent of subsurface contamination and the potential for in situ bioventing. The procedures outlined in this section assist in the collection and interpretation of soil gas information, with the ultimate goal of promoting a more cost-effective approach to fuel-contaminated soil remediation

1.2.1 Soil Gas Chemistry

The chemical composition of soil gas can vary considerably from atmospheric composition as a result of biological and mineral reactions in the soil. Many compounds and elements may be present in soil gas because of site-specific geochemistry, but three indicators are of particular interest for bioventing systems: respiration gases (oxygen and carbon dioxide) and hydrocarbon vapors. The soil gas concentrations of these indicators in relation to atmospheric air and uncontaminated background soils can provide valuable information on the ongoing natural biodegradation of hydrocarbon contaminants and the potential for bioventing to enhance the rate of natural biodegradation.

1.2.1.1 Respiration Gases

Oxygen serves as a primary electron acceptor for soil microorganisms employed in the degradation of both refined and natural hydrocarbons. Following a hydrocarbon spill, if active microbial populations are present, soil gas oxygen concentrations are usually low (typically less than 5 percent) and soil gas carbon dioxide (a metabolite of hydrocarbon degradation) may be high (typically greater than 10 percent). Oxygen concentrations generally are lower in the vicinity of the contaminated soils than in clean soils, indicating that aerobic biodegradation is depleting oxygen. As the population of fuel-degrading microorganisms increases, the supply of soil gas oxygen is often depleted, creating an anaerobic volume of contaminated soil. Under anaerobic conditions, fuel biodegradation generally proceeds at significantly slower rates than when oxygen is available for metabolism. In some cases, aerobic biodegradation continues because the diffusion or advection of oxygen into soils from the atmosphere exceeds biological oxygen utilization rates. Under these circumstances, the site is naturally aerated, and the hydrocarbons are naturally attenuated over time.

Carbon dioxide is produced as a by-product of the complete aerobic biodegradation of hydrocarbons and can also be produced or buffered by the soil carbonate cycle (Ong et al., 1991). Carbon dioxide levels in soil gas are generally elevated in fuel contaminated soils compared with levels in clean background soils. In many soils, higher carbon dioxide concentrations correlate with low oxygen levels; however, this is not always true. Because of the buffering capacity of alkaline soils, the relationship between contaminant biodegradation and carbon dioxide production is not always a reliable indicator. Carbon dioxide can form carbonates rather than gaseous carbon dioxide, particularly in soils with pH over 7.5 and high reserve alkalinity. In acidic soils, such as exist at Tyndall AFB, Florida, carbon dioxide production is directly proportional to oxygen utilization (Miller and Hinchee, 1990).

Soil gas survey results in a contaminated area should be compared with those obtained from an uncontaminated area. Typically, soil gas concentrations in an uncontaminated area are significantly different, with oxygen concentrations approximately equal to ambient concentrations and very low carbon dioxide (less than 0.5 percent).

1.2.1.2 Hydrocarbon Vapors

Volatile hydrocarbons found in soil gas can also provide valuable information on the extent and magnitude of subsurface contamination. Fuels such as gasoline, which contain a significant fraction of C_6 and lighter compounds, are easily detected using soil gas monitoring techniques. Heavier fuels, such as diesel, contain fewer volatiles and are more difficult to locate based on volatile hydrocarbon monitoring. Methane is frequently produced as a by-product of anaerobic biodegradation and, like oxygen depletion, has been used to locate the most contaminated soils at a site. Extensive literature is available on soil gas survey techniques for using volatile hydrocarbons as indicators of contamination (Rivett and Cherry, 1991; Downey and Hall, 1994).

1.2.2 Collection and Analysis of Soil Gas Samples

This section describes the test equipment and methods used to conduct field soil gas surveys, to monitor soil gas for bioventing systems, and to install temporary soil gas monitoring points. The procedures and equipment described in this section are only guidelines. Because of widely varying site conditions, site-specific applications are necessary. In some regulatory jurisdictions, soil gas survey monitoring points must comply with well installation or other regulations.

Whenever possible, soil gas surveys should be conducted at potential bioventing sites before locating the pilot test vent well(s) and monitoring points. The soil gas survey is used to determine the necessity of bioventing whether anaerobic soil gas conditions exist and by providing an initial indication of the extent of contamination. If sufficient oxygen is naturally available and distributed throughout the subsurface, bioventing may not enhance biodegradation rates. The soil gas survey can also help to determine the areal extent and, in the case of shallow contamination, the vertical extent of soil contamination. Information about contaminant distribution helps to locate the vent well and soil gas monitoring points and to determine the optimum depths of screened intervals.

The soil gas survey points should be arranged in a grid pattern centered on the known or suspected contaminated area. The soil gas probes are positioned at each grid intersection, and the survey begins near the center of the grid and progresses outward to the limits of significant detectable soil contamination. At times, soil gas measurements are taken at several depths at each location to determine the vertical distribution of contamination and oxygen supply. At shallow sites, a soil gas sampling grid should be completed with samples collected from multiple depths if the contaminated interval exceeds 3 ft (0.91 m) or if contamination is suspected in different soil types.

A soil gas survey can be conducted using small-diameter (typically 5/8- to 1-in. [1.6- to 2.5-cm] outside diameter steel probes. The typical probe consists of a drive point with a perforated tip that is threaded onto a series of drive rod extensions. Figure 1-3 shows a typical setup for monitoring soil gas.[2]

Soil conditions and depth of contamination dictate the method of probe installation. Utility clearances from the local utility companies and digging permits (required at

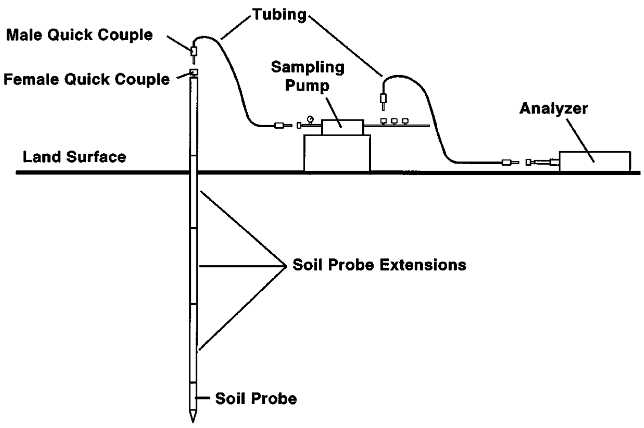


Figure 1-3. Schematic of a soil gas sampling system using the stainless steel soil gas probe.

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[2] See Appendix B for recommended specifications and manufacturers for soil gas sampling equipment.

military installations) should be obtained before probe installation. Temporary probes are installed using either a handheld electric hammer or a hydraulic ram. The maximum depth for hammer-driven probes is typically 10 ft to 15 ft (3 m to 4.6 m), depending on soil texture. Hydraulic rams are capable of driving the probes over 30 ft (9.1 m) in a variety of soil conditions. If hydraulic rams are not sufficient, a GeoProbe or similar equipment can be used and also can collect soil samples.

At sites with deeper contamination, where soil texture precludes the use of a hammer or hydraulic ram or where a permanent monitoring system is required, permanent soil gas monitoring points may be installed using either a portable or a truck-mounted drill rig.

Gaseous concentrations of carbon dioxide and oxygen can be analyzed using an oxygen/carbon dioxide analyzer. The analyzer generally has an internal, battery-powered sampling pump and range settings of 0 percent to 25 percent for both oxygen and carbon dioxide. Before taking measurements, the analyzer should be checked for battery charge level; it should also be calibrated daily using atmospheric concentrations of oxygen and carbon dioxide (20.9 percent and 0.05 percent, respectively) and a gas standard containing 0.0 percent oxygen and 5.0 percent carbon dioxide, and 95 percent nitrogen.

Several types of instruments are available for field measurement of TPH concentrations in air. The selected instrument must be able to measure hydrocarbon concentrations in the range of 1 to 10,000 parts per million, volume per volume (ppmv) and be able to distinguish between methane and nonmethane hydrocarbons. Flame ionization detectors are the most accurate field screening instruments for fuel hydrocarbons. Instruments using a platinum catalyst detector system are also acceptable and are easier to use in the field. Photoionization detectors are not recommended for the high levels of volatile hydrocarbons found at many sites. Before taking measurements with any field instrument, the battery charge level should be checked and the analyzer should be calibrated against a hexane calibration gas to ensure proper operation.

The analyzer should also have a selector switch to change the response to eliminate the contribution of methane gas to the TPH readings. Methane gas is a common constituent of anaerobic soil gas and is generated by degrading manmade hydrocarbons or natural organics. Methane is commonly produced in swampy areas or in fill areas containing organic material. If methane is not excluded from the TPH measurement, TPH results may indicate erroneously high levels of petroleum hydrocarbon contamination in the soil. The methane content can also be estimated by placing a large carbon trap in front of the hydrocarbon analyzer. The carbon retains the heavier hydrocarbons, while methane and other lighter molecular weight hydrocarbons pass through to the detector.

Electric motor-driven sampling pumps are used to purge and collect samples from monitoring points and soil gas probes. The pumps should be either oil-less rotary-vane or diaphragm pumps capable of delivering approximately 1 cubic ft per minute (cfm) (28 L/min) of air at a maximum vacuum of 270″H_2O (6.7×10^4 Pa). The pumps have oil-less filters to eliminate particulates from the air stream. Low-flow, battery-operated pumps may be favored in high-permeability soils to minimize short-circuiting.

Differential vacuum gauges are used to monitor the vacuum in the sampling point during purging and as an indicator of relative permeability. Typical vacuum ranges of the gauges are 0 to 50″H_2O (0 to 1.2×10^4 Pa) and 0 to 250″H_2O (6.2×10^4 Pa) for sites with sandy and clayey soils, respectively.

Purging the soil gas probe is a prerequisite for obtaining representative soil gas samples. A typical purging system consists of a 1-cfm (28-L/min) sampling pump, a vacuum gauge, and an oxygen/carbon dioxide meter. The vacuum side of the pump is connected to the soil gas probe. A vacuum gauge is attached to a tee in the vacuum side of the system to monitor the vacuum produced during purging, and the oxygen/carbon dioxide analyzer is connected to a tee in the outlet tubing to monitor oxygen/carbon dioxide concentrations in the extracted soil gas. The magnitude of vacuum measured during purging is inversely proportional to soil permeability and determines the method of sample collection.

After the purging system is attached to the soil gas probe or monitoring point, the valve or hose clamp is opened and the pump is turned on. Purging continues until oxygen and carbon dioxide concentrations stabilize, indicating the purging is complete. Before turning off the pump, a hose clamp or valve is used to close the sampling tubing to prevent fresh air from being drawn into the soil gas probe.

Sampling methods for high-permeability soils (sand and silt) should be followed if the vacuum measured during purging is less than 10″H_2O (2.5×10^3 Pa). Soil gas sampling and analysis are performed using the same equipment used for purging, minus the vacuum gauge. After opening the sampling point valve or hose clamp, the sampling pump is turned on, and the extracted soil gas is analyzed for stable oxygen/carbon dioxide and TPH concentrations.

A different sampling procedure can be followed to collect soil gas samples from low-permeability soils. The higher vacuums required for sampling increase the risk of vacuum leaks introducing fresh air and diluting the soil gas sample. One method that may be used in low-permeability soils is described below.

After purging the sampling point, a soil gas sample is collected in a Tedlar bag before analysis. The evacuated Tedlar bag should be placed inside an airtight chamber. The chamber is then connected to the sampling point via a hose barb that passes through the chamber wall. The chamber is then closed, sealed, and connected to the pump inlet with flexible tubing. The sampling system is shown in Figure 1-4. To collect the sample, the monitoring point valve is opened, the pump is turned on, and the pressure relief port on the chamber is sealed using either a valve or the sampler's finger. The partial vacuum within the chamber created by the pump draws soil gas into the Tedlar bag. When the Tedlar bag is nearly filled, the sampling point valve or hose clamp is closed, and the pump is turned off. The chamber is then opened, the Tedlar bag valve is closed, and the bag is removed from the chamber. The soil gas sample is then analyzed by attaching the oxygen/carbon dioxide and TPH analyzers directly to the Tedlar bag. The advantage of this method is that the sampling pump is no longer in line, thereby minimizing the sampling train and subsequent sample dilution.

Most problems encountered during soil gas sampling and purging can be divided into three categories: (1) difficulty extracting soil gas from the sampling point, (2) water being drawn from the sampling point, and (3) high oxygen readings in areas of known soil contamination. Some of the more common problems and solutions are discussed below.

Difficulty extracting soil gas from a sampling point is typically caused by low-permeability (clayey and/or nearly saturated) soils. Collecting soil gas samples from low-permeability soils is facilitated by slowing the soil gas extraction rate, which allows the use of less vacuum. Difficulty extracting soil gas from a soil gas probe can also be caused by the screen being fouled by fine-grained soil or heavy petroleum residuals. The probe should be removed from the soil, and the screen should be either cleaned or replaced if visibly fouled.

Water being drawn from the sampling point by the purge pump may be the result either of the point being installed in the saturated zone or, in the case of permanent monitoring points, the filter pack being saturated with water during construction. In the former case, a temporary probe can be pulled up to a shallower depth above the saturated zone and resampled. With a permanent monitoring point installed within the saturated zone, sampling must be delayed until either the water table drops because of seasonal variations or the water table is artificially depressed by a dewatering operation.

If the screened interval in a permanent monitoring point is installed above the saturated zone but the filter pack was saturated with water during construction, sampling may still be possible if the water is pumped from the monitoring point. This method will only work if the screened interval is at a depth of less than approximately 22 ft (6.7 m), which is the practical limit of suction lift.

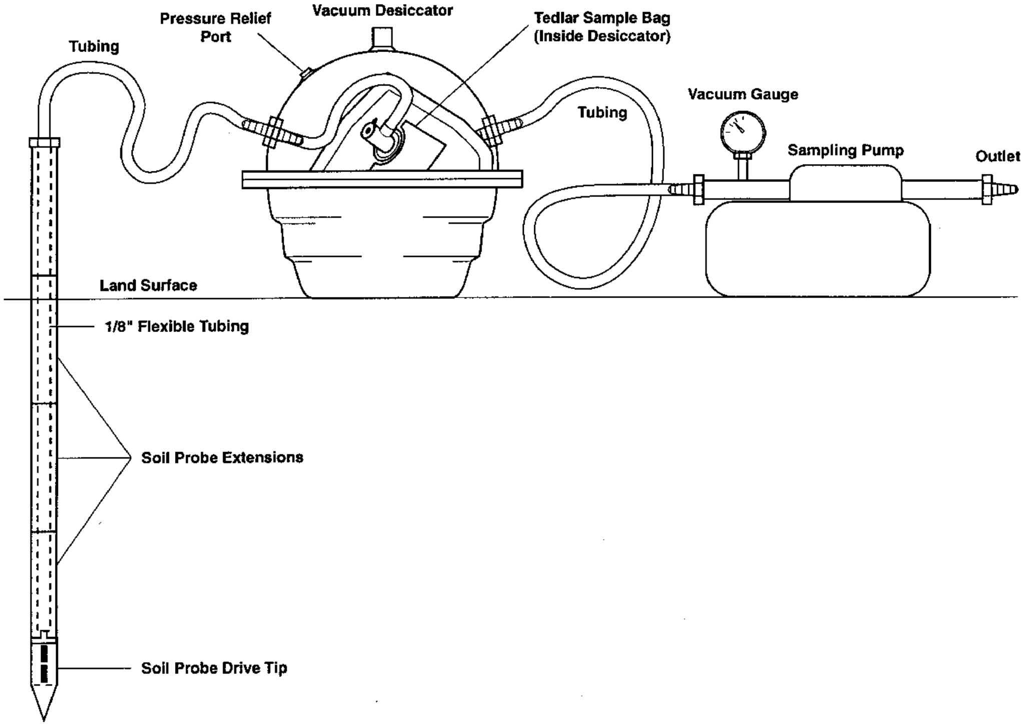

Figure 1-4. Schematic of a soil gas sampling system for collection of soil gas from low-permeability soils.

Water also may be drawn into the point in unsaturated soils as the result of the creation of a vacuum in excess of capillary pressure. In this case, the extracted flow typically is a mixture of water and soil gas. Frequently, a water trap before the sampling pump can be used to remove the water; thus, collecting and analyzing a soil gas sample is still possible.

High soil gas oxygen readings in areas of known soil contamination may indicate a leak in the sampling or purging system. The potential for leakage, and the resulting dilution of the sample with atmospheric air, is higher in low-permeability soils where higher vacuums are required for purging and sampling. If a leak is suspected, all connections in the sampling system and the seal around the monitoring point or soil gas probe should be inspected for leaks. Seals around a soil gas probe or monitoring point can be checked for leaks by inspecting for air bubbles while injecting air with a sampling pump after adding water around the probe or monitoring point. Any observed or suspected leaks should be corrected by tightening connections, repositioning the soil gas probe, or attempting to repair the monitoring point seal.

1.2.3 Interpretation of Soil Gas Survey Results

The purpose of gathering soil gas data during bioventing investigations is to locate areas where addition of oxygen will most efficiently enhance fuel biodegradation. Low soil gas oxygen concentrations are a preliminary indication that bioventing may be feasible at the site, so proceeding to in situ respiration testing is appropriate. If soil gas oxygen concentrations are high (greater than 5 percent to 10 percent), yet contamination is present, other factors may be limiting biodegradation. The most common limiting factor is low moisture level. If a pilot test is to be completed, the soil gas survey should focus on locating areas with the lowest oxygen concentrations. For full-scale applications, it is useful to determine the entire areal extent and depth of soils with an oxygen deficit (for practical purposes, less than 5 percent oxygen).

In very shallow, permeable soils, diffusion, biometric pumping, or water table fluctuations may enhance air movement into the soil and provide a natural oxygen supply.[3] Soil gas data are useful for determining which sites are naturally aerated and therefore do not require mechanical bioventing systems.

If high oxygen concentrations are observed on the site, the existence of significant contamination should be questioned. Lower levels of contamination (e.g., less than 1,000 mg/kg TPH) could potentially be biodegraded by the natural oxygen supply, and no active remediation would be necessary. If higher levels of hydrocarbons are present (above 1,000 mg/kg), the natural oxygen supply will likely be inadequate to sustain biodegradation and, more likely, some other factor is limiting. In the authors' experience, soil containing both high oxygen and high hydrocarbon concentrations only occurs at moisture-limited sites (the most common case) or sites with toxicity problems (trichloroethylene [TCE] in one case and phenolics in another). In only two cases familiar to the authors, these factors could not explain the lack of oxygen utilization. This occurred at a JP-5 jet fuel site on Fallon Naval Air Station (NAS) in Nevada and a JP-4 Spill Site at Davis-Monthan AFB in Arizona. The problem sites are not moisture limited; however, no clear explanation has arisen to date (Engineering-Science, 1994; Kittel et al., 1995). A series of examples of soil gas survey results and an interpretation of the data are presented here to illustrate the principles discussed in this section.

Example 1-2. Soil Gas Survey Conducted at Keesler AFB: At the site described in Example 1-1, a soil gas survey was conducted. First, depth to ground water and free product thickness were measured at all of the ground-water monitoring wells (MWs). Ground-water depths were as follows: MW8-1 at 6.8 ft (2.1 m), MW8-2 at 8.0 ft (2.4 m), MW8-3 at 8.2 ft (2.5 m), and MW8-11 at 8.25 ft (2.5 m). No free product was detected in any of the wells, so free product removal was not a factor at this site.

A limited soil gas survey was conducted because the area of contamination had recently been defined. Soil gas samples were collected at depths ranging from 2 ft to 6 ft (.61 m to 1.8 m). Because ground water was measured at 6.8 ft (2.1 m), soil gas probes were not driven deeper.

Results from this survey are shown in Table 1-1. At most locations, oxygen was limiting, with concentrations less than 5 percent, and carbon dioxide and TPH concentrations were relatively high. The exception was at location SGS-D-6.0'. At this point, oxygen was measured at 20.1 percent, carbon dioxide at 0.1 percent, and TPH at 120 ppm. These levels were more representative of ambient air than of the soil gas concentrations measured at other points at the site, indicating that significant dilution of this sample may have occurred. Because of these measurements, the sampling pump was thoroughly examined and loose connections were tightened. Upon resampling, soil gas concentrations were more representative of other soil gas concentrations. If resampling were to give the same initial results, it could be possible that this monitoring point was plugged, causing the sampling train to leak, and/or atmospheric air was short circuiting

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[3] See Volume I for a discussion of factors affecting the bioventing process.

Table 1-1. Results From a Soil Gas Survey at AOC A, Keesler AFB, Mississippi

Soil Gas Survey Point	Depth (ft)	Oxygen (%)	Carbon Dioxide (%)	TPH (ppmv)
SGS-A	2.0	4.8	9.8	>100,000
	4.0	0.3	12	>100,000
	6.0	0.5	11	>100,000
SGS-B	2.0	1.5	12	>100,000
	4.0	0.5	12	>100,000
	6.0	0.9	12	>100,000
SGS-C	2.0	0.4	11	28,000
	4.0	0.8	11	30,000
	6.0	0.4	11	32,000
SGS-D	2.0	0.4	11	47,000
	4.0	0.3	11	56,000
	6.0	20.1	0.1	120
	6.0	0.4	11	60,000

SOS = Soil gas survey.

to the point. In either case, results from this point should be discarded as invalid.

Results of this soil gas survey indicate that this site is an excellent candidate for bioventing.

Example 1-3. Soil Gas Survey at Building 1813, Hanscom AFB, Massachusetts: This site comprises an underground storage tank (UST) containing diesel fuel that had leaked. The tank was removed, but an unknown quantity of fuel-contaminated soil remained at the site. Site soils are sandy to ground water, which occurred at 8 ft to 9 ft (2.4 m to 2.7 m).

A soil gas survey was conducted at seven locations and at multiple depths. Soil gas results are presented in Table 1-2.

Low levels of TPH indicate that little diesel-contaminated soil remained at the site or that residual fuels were highly weathered. Near-atmospheric oxygen levels at all depths indicated that remaining hydrocarbons were being biodegraded with oxygen supplied by natural diffusion. Carbon dioxide was found at levels above the atmospheric concentration of 0.03 percent, indicating some biological respiration was occurring. Higher carbon dioxide levels and slightly depressed oxygen levels at point 3 (PT3) and PT4 indicated remaining fuel was probably located in this area of the site. Natural aeration appeared to provide sufficient oxygen for biodegradation of remaining fuel residuals.

Table 1-2. Results From a Soil Gas Survey at Building 1813, Hanscom AFB, Massachusetts

Soil Gas Survey Point	Depth (ft)	Oxygen (%)	Carbon Dioxide (%)	TPH (ppmv)
PT1	3.0	20.5	0.8	62
PT2	3.0	20.5	1.0	60
	6.0	20.6	0.5	42
PT3	3.0	19.0	2.0	80
	6.0	19.0	2.0	78
PT4	3.0	19.2	2.2	80
	6.0	19.0	2.4	93
PT6	3.0	20.5	0.8	46
	6.0	20.5	0.8	44
PT7	3.0	20.0	0.5	82
	6.0	19.8	1.5	61
	7.0	19.0	1.0	70
PT8	6.0	19.5	1.5	60
	8.0	20.5	0.5	48

Example 1-4. Soil Gas Survey at the Aquasystem Site, Westover AFB, Massachusetts: This site consisted of USTs that, when removed, revealed soil contamination. An unknown quantity of mixed fuels contamination remained in the soil. Site soils were predominantly sand, with ground water at approximately 13 ft (4.0 m) below the surface.

A soil gas survey consisting of a 12-point grid was completed in and downgradient of the former tank pit. All points were sampled at multiple depths. Results of the survey are provided in Table 1-3.

Low levels of TPH were detected in the soil gas at this site. Oxygen levels were significantly depleted below atmospheric concentrations in soils near PT7 and PT17, and generally decreased with depth. The 8 percent to 9 percent of oxygen available in this area, however, was more than sufficient to sustain in situ biodegradation. Carbon dioxide ranged from 2 percent to 8.5 percent and generally increased with depth. The available data suggested that significant natural biodegradation was occurring at the site. More oxygen-depleted soil might exist in the capillary fringe, and engineered bioventing could accelerate biodegradation if this anaerobic zone exists. The decision to biovent this site should be based on other factors, such as the impact and potential risk that soil contamination poses to ground water.

Table 1-3. Results from a Soil Gas Survey at the Aquasystem Site, Westover AFB, Massachusetts

Soil Gas Survey Point	Depth (ft)	Oxygen (%)	Carbon Dioxide (%)	TPH (ppmv)
PT1	3.0	16	3.2	60
	6.0	12.5	5	60
PT2	3.0	15.5	4.3	72
	6.0	13	6	74
PT3	3.0	18	2.6	74
	6.0	12	6.2	84
PT4	3.0	16	4	86
	6.0	11.5	5	80
PT5	3.0	14.8	4	76
	6.0	11	5.2	72
PT7	3.0	14	7	105
	6.0	8.5	8.5	69
PT8	3.0	12	5.5	75
	6.0	11	6.5	76
PT9	3.0	11.5	6	90
	6.0	11	6.2	78
PT11	3.0	16	3.5	84
	6.0	15	4	94
PT12	3.0	18.5	2.5	80
	6.0	15.5	4.2	91
	9.0	15	4.8	90
	12.0	13	5.6	92
PT16	6.0	17	2	94
	7.5	13	3.5	80
PT17	6.0	11.8	6.5	92
	9.0	11	6.5	96

Example 1-5. Soil Gas Survey at an Oil/Water Separator Leak at Cape Canaveral AFS, Florida: This site consisted of an oil/water separator leak located near a diesel transfer station at Cape Canaveral AFS, Florida. Site soils consisted of sandy soil with shell fragments. Ground water was approximately 6 ft (1.8 m) below the surface.

A soil gas survey was conducted at eight locations. An attempt was made to sample soil gas at two depths. Soil gas results are presented in Table 1-4.

Table 1-4. Results From a Soil Gas Survey at an Oil/Water Leak at Cape Canaveral AFS, Florida

Soil Gas Survey Point	Depth (ft)	Oxygen (%)	Carbon Dioxide (%)	TPH (ppmv)
PT1	2.5	15.5	4.0	82
	5.5	12.5	6.0	82
PT2	2.5	14.0	5.0	76
	5.5	5.5	9.5	77
PT3	2.5	13.0	5.5	73
	5.5	10.0	7.0	75
PT4	2.5	19.0	2.0	60
	5.5	18.5	2.5	66
PT5	2.5	19.5	1.0	57
	5.5	19.0	2.0	60
PT6	2.5	18.5	2.5	64
	5.5	17.5	3.0	74
PT7	2.5	20.0	1.0	36
	5.5	20.0	1.0	35
PT8	2.5	20.5	0.5	34
	5.5	20.2	0.8	43

Low levels of TPH indicate that little diesel-contaminated soil remained at the site or it was highly weathered. Oxygen levels were significantly depleted near PT2 and generally decreased with depth in points near the oil/water separator. Carbon dioxide levels were elevated in areas with low oxygen, indicating that in situ biodegradation was proceeding in the vicinity of the oil/water separator. More oxygen-depleted soil might exist in the capillary fringe, and engineered bioventing could accelerate biodegradation, if this anaerobic zone exists. The decision to biovent this site should be based on other factors, such as the impact and potential risk that soil contamination poses to ground water. One additional note: if the oil/water separator were connected to a sanitary line, the biological oxygen demand might be the result of leaking sewage. An analysis of soil gas for benzene, toluene, ethylbenzene, and total xylenes (BTEX) could help to determine if the oxygen demand were fuel related.

1.3 Soil Characterization

Soil characterization is a crucial component of the site characterization process. Of primary importance is determining the concentration and distribution of contaminants. Because of large variations in the distribution of contaminants at a site, a relatively large number of soil samples must be collected to adequately delineate the vertical and lateral extent of contamination. Described in the following sections are techniques for locating and drilling soil borings.[4] The soil analytical protocol is also discussed.

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[4] See Appendix B for recommended specifications and manufacturers for the soil sampling equipment.

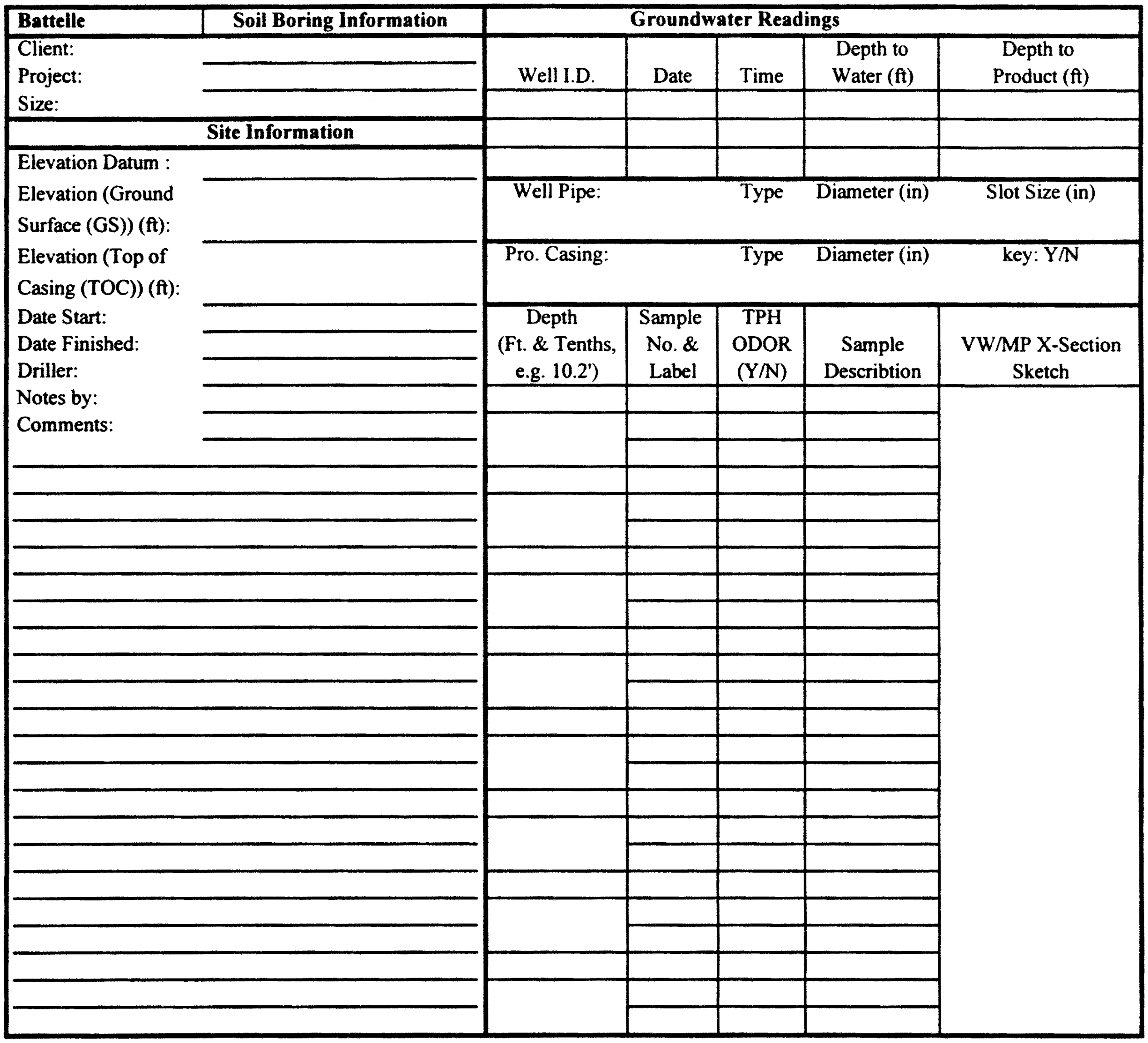
1.3.1 Soil Borings

Soil borings should be located based on either the review of existing site data or the results of the soil gas survey. Soil borings can serve two purposes: the collection of soil samples and the installation of vent wells and monitoring points. Soil borings have the advantage of allowing for collection of many soil samples from a single location and allowing for subsequent installation of the vent wells and monitoring points in the borings. Disadvantages include the generation of soil cuttings and the fact that drilling may require subcontracting and a large amount of time. Alternative methods, such as a GeoProbe system or cone penetrometer, may be used for collection of soil samples and may be suitable for installing soil gas monitoring points.

The hollow-stem auger method is generally preferred for drilling in unconsolidated soils; however, a solid-stem auger also is acceptable in more cohesive soils. The final diameter of the borehole depends on the diameter selected for the vent wells but typically should be at least two times greater than the vent well's outside diameter.

All drilling and sample collection activities should be observed and recorded on a geologic boring log (Figure 1-5) to record soil sample interval, sample recovery, visual presence (or absence) of contamination, soil description, and lithology. Soil samples should be labeled and properly stored immediately after collection. An example procedure for soil sample collection, labeling, packing, and shipping is provided in Appendix C.

All boreholes should preferably be completed as vent wells or monitoring points. If this is not possible, boreholes must be abandoned according to applicable state or federal regulations. Typically, borehole abandonment is accomplished by backfilling with bentonite or grout.



Battelle **Soil Boring Information**

Client:
Project:
Size:

Site Information

Elevation Datum :
Elevation (Ground Surface (GS)) (ft):
Elevation (Top of Casing (TOC)) (ft):
Date Start:
Date Finished:
Driller:
Notes by:
Comments:

Groundwater Readings

Well I.D.	Date	Time	Depth to Water (ft)	Depth to Product (ft)

Well Pipe:	Type	Diameter (in)	Slot Size (in)
Pro. Casing:	Type	Diameter (in)	key: Y/N

Depth (Ft. & Tenths, e.g. 10.2')	Sample No. & Label	TPH ODOR (Y/N)	Sample Describtion	VW/MP X-Section Sketch

Figure 1-5. Sample soil boring log.

1.3.2 Soil Analyses

A summary of soil analyses is provided in Table 1-5. Methods in this table are not the only methods available but are those currently used by the Air Force currently uses. Based on results from the Bioventing Initiative, recommended parameters to be measured include the aromatic hydrocarbons (BTEX), TPH, moisture content, and particle size. Total Kjeldahl nitrogen (TKN) was found to be a statistically significant factor in the statistical analyses of Bioventing Initiative data;[5] however, no evidence exists to date that addition of nitrogen enhances site remediation. Therefore, an analysis for TKN is only recommended if all other explanations for poor bioventing performance have been exhausted (i.e., permeability, moisture content).

Measurements of BTEX and TPH are necessary for delineation of the contaminant plume. In addition, BTEX and TPH typically are of regulatory concern; therefore, these concentrations must be established.

Moisture content has been found to limit biodegradation in extreme environments. At a site in California, moisture content averaged approximately 2 percent and irrigation substantially improved biodegradation rates.[6]

TKN is a nutrient required for microbial growth and respiration. Low TKN levels may affect microbial respiration; however, although a statistically significant relationship has been observed between TKN and oxygen utilization rates, the relationship is weak and unlikely to have practical significance.

Particle size distribution is an important indicator of permeability. High clay content soils may be difficult to biovent because of the inability to move air through the soil, particularly when high moisture levels exist. In addition, clay particles can be sites of significant contaminant adsorption and as such can significantly affect contaminant sorption and bioavailability.

1.4 In Situ Respiration Testing

The in situ respiration test was developed to provide rapid field measurement of in situ biodegradation rates to determine the potential applicability of bioventing at a contaminated site and to provide information for a full-scale bioventing system design. This section describes the test as developed by Hinchee and Ong (1992). This respiration test has been used at numerous sites throughout the United States, including all Bioventing Initiative sites. The in situ respiration test described in this document is essentially the same, with minor modifications.

1.4.1 In Situ Respiration Test Procedures

The in situ respiration test consists of placing narrowly screened soil gas monitoring points into the unsaturated zone of contaminated soils and venting these soils with air containing an inert tracer gas (typically helium) for a given period. The apparatus for the respiration test is illustrated in Figure 1-6.[7] An example procedure for conducting an in situ respiration test is provided in Appendix C.

As part of the Bioventing Initiative, respiration rates in uncontaminated areas of similar geology to the contaminated test site were evaluated. These results showed that measurement of background respiration rates was not necessary because little significant respiration had

Table 1-5. Soil Analyses[a] Based on Bioventing Initiative Results

Analysis	Method	Comments	Sample Volume, Container, Preservation	Field or Analytical Laboratory
Aromatic hydrocarbons (BTEX)	Purge and trap GC method SW8020	Handbook method	Collect 100 g of soil in a glass container with Teflon-lined cap or in brass sleeves[b]; cool to 4°C	Analytical laboratory
TPH	Modified GC method SW8015	Handbook method; reference is the California LUFT[c] manual	Collect 100 g of soil in a glass container with Teflon-lined cap or in brass sleeves[b]; cool to 4°C	Analytical laboratory
Moisture content	ASTM D-2216	Handbook method	Collect in a 4-oz glass container with Teflon-lined cap	Analytical laboratory
TKN[d]	EPA 351.4	Handbook method	Collect in a 4-oz glass container with Teflon-lined cap	Analytical laboratory

[a] Recommended soil analysis is based on experience and analyses of petroleum-contaminated sites. Additional data may be required at sites contaminated with other compounds.
[b] One sample in the brass sleeves provides sufficient volume for analyses of both aromatic hydrocarbons and TPH.
[c] LUFT = State of California *Leaking Underground Fuel Tank Field Manual*, 1988 edition.
[d] Not recommended for an initial analysis but only if bioventing performance is poor and other factors such as permeability and moisture content do not account for the poor performance.

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[5] See Chapter 5 of Volume I for a discussion of the statistical analyses of Bioventing Initiative data.

[6] See Section 3.2.2.2 of Volume I for a discussion of this site.

[7] See Appendix B for recommended specifications and manufacturers for the in situ respiration testing equipment.

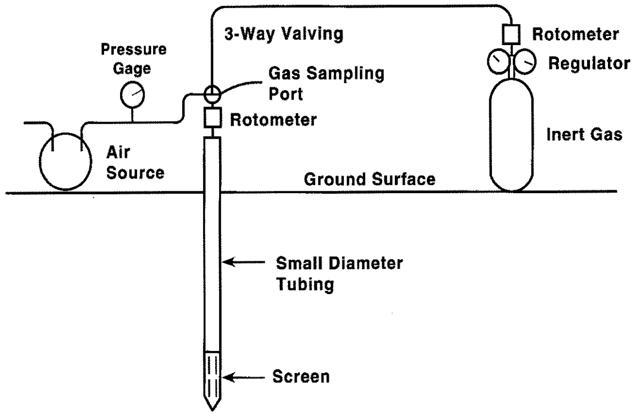

Figure 1-6. In situ respiration test apparatus.

occurred. Instead, oxygen and carbon dioxide should be measured in an uncontaminated location of similar geology. Only if these measurements indicate significant oxygen depletion should a background in situ respiration test be conducted to determine whether significant background respiration is occurring.

In a typical experiment, a cluster of three to four soil gas probes are placed in the contaminated soil of the test location. These soil gas probes must be located in the center of contaminated areas where low soil gas oxygen concentrations and high TPH concentrations have been measured. If the monitoring points are not located in contaminated areas, the in situ respiration test will not produce meaningful results. Additional detail on monitoring point location and construction is provided in Section 2.6.

Measurements of carbon dioxide and oxygen concentrations in the soil gas are taken before air and inert gas injection. A 1 percent to 3 percent concentration of inert gas is added to the injection air, which is injected for approximately 24 hours at flow rates ranging from 1.0 cfm to 1.7 cfm (28 L/min to 48 L/min). The air provides oxygen to the soil, and the inert gas measurements provide data on the diffusion of oxygen from the ground surface and the surrounding soil and ensure that the soil gas sampling system does not leak. The background control location is placed in similar soils in an uncontaminated area to monitor natural background respiration rates.

After air and inert gas injection are turned off, oxygen, carbon dioxide, and inert gas concentrations are monitored over time. Before a reading is taken, the probe is purged for a few minutes until the carbon dioxide and oxygen readings are constant. Initial readings are taken every 2 hours and then progressively over 4-hour to 8-hour intervals. If oxygen uptake is rapid, more frequent monitoring may be required. If it is slow, less frequent readings may be acceptable. The experiment usually is terminated when the soil gas oxygen concentration is approximately 5 percent.

As discussed in Section 1.2, shallow monitoring points pose a risk of pulling in atmospheric air in the process of purging and sampling. Excessive purging and sampling may result in erroneous readings. Oversampling produces no benefits and, when sampling shallow points, care must be taken to minimize the volume of air extraction. In these cases, a low-flow extraction pump of about 0.03 cfm to 0.07 cfm (0.85 L/min to 2.0 L/min) should be used.

1.4.2 Interpretation of in Situ Respiration Test Results

Oxygen utilization rates are determined from data obtained during the in situ respiration test. The rates are calculated as the zero-order relationship between percentage of oxygen versus time. Typically, a rapid linear decrease in oxygen occurs, followed by a lag period once oxygen concentrations drop below approximately 5 percent. To calculate oxygen utilization rates, only the first linear portion of the data is used because this represents oxygen utilization when oxygen is not limiting, as is the case during active bioventing.

To estimate biodegradation rates of hydrocarbon from the oxygen utilization rates, a stoichiometric relationship for the oxidation of the contaminant is used. For hydrocarbons, hexane is used as the representative hydrocarbon. If a site is contaminated with compounds other then petroleum hydrocarbons, a suitable compound should be used to determine stoichiometry. The stoichiometric relationship used to determine petroleum degradation rates is:

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

Based on the utilization rates (percentage of oxygen per day), the biodegradation rate in terms of mg hexane-equivalent per kg of soil per day is estimated using Equation 1-2:

$$-k_B = \frac{-\dfrac{k_o}{100}\,\theta_a\,\dfrac{1\text{L}}{1{,}000\text{ cm}^3}\,\rho_{O_2}\,C}{\rho_k\left(\dfrac{1\text{ kg}}{1{,}000\text{ g}}\right)} = \frac{-k_o\,\theta_a\,\rho_{O_2}\,C\,(0.01)}{\rho_k} \qquad \text{(Eq. 1-2)}$$

where:

k_B = biodegradation rate (mg/kg-day)

k_o = oxygen utilization rate (%/day)

θ_a = gas-filled pore space (volumetric content at the vapor phase, m^3 gas/cm^3 soil)

ρ_{O_2} = density of oxygen (mg/L)

C = mass ratio of hydrocarbons to oxygen required for mineralization (1:3.5)

ρ_k = soil bulk density (g/cm^3)

These terms may be derived through either direct measurement or estimation. The oxygen utilization rate, k_o, is directly measured in the in situ respiration test. The ratio of hydrocarbons to oxygen required for mineralization, C, can be calculated based upon stoichiometry (see Equation 1-1 for hexane) but generally falls between 0.29 and 0.33. This neglects any conversion to biomass, which probably is small and difficult, if not impossible, to measure. The density of oxygen may be obtained from a handbook for a given temperature and pressure, or calculated from the ideal gas law. Table 1-6 provides some useful oxygen density information. The bulk density of soil is difficult to measure accurately because of the difficulty in collecting an undisturbed sample; however, it may be reasonably estimated from the literature. Table 1-7 lists useful literature values for bulk density.

Table 1-6. Oxygen Density Versus Temperature

Temperature (°C)	Temperature (°F)	Density (mg/L)[a]	Density (lb/ft^3)[a]
-33	-27.4	1,627[b]	0.10[b]
-3	26.6	1,446[c]	0.090[c]
0	32	1,429[c]	0.089[c]
5	41	1,403[c]	0.088[c]
10	50	1,378[c]	0.086[c]
15	59	1,354[c]	0.084[c]
20	68	1,331[c]	0.083[c]
27	80.6	1,301[b]	0.082[b]
30	86	1,287[c]	0.080[c]
35	95	1,266[c]	0.079[c]
40	104	1,246[c]	0.078[c]
57	134.6	1,182[b]	0.074[b]
87	188.6	1,083[b]	0.067[b]
127	260.0	975[b]	0.061[b]

[a] Oxygen density at standard pressure.

[b] Density values from Braker and Mossmon (1980).

[c] Density calculated using the second viral coefficient to the equation of state for oxygen gas:

$$P = \frac{RT}{V}\left[1 + \frac{B(T)}{V}\right]$$

where P = pressure (atm), R = gas constant, V = molar volume, and B = second viral coefficient. The temperature dependence of B was calculated from:

$$B(T) = \sum_{i=1}^{n} A_i \left[\frac{T_0}{T} - 1\right]^{i-1}$$

The constants A^i were obtained from Lide and Kehianian (1994).

Table 1-7. Bulk Density of Various Soils[a]

Soil Description	Porosity	Soil Bulk Density ρ_κ (dry g/cm^3)
Uniform sand, loose	0.46	1.43
Uniform sand, dense	0.34	1.75
Mixed-grain sand, loose	0.40	1.59
Mixed-grain sand, dense	0.30	1.86
Windblown silt (loess)	0.50	1.36
Glacial till, very mixed-grained	0.20	2.12
Soft glacial clay	0.55	1.22
Stiff glacial clay	0.37	1.70
Soft slightly organic clay	0.66	0.93
Soft very organic clay	0.75	0.68
Soft montmorillonitic clay (calcium bentonite)	0.84	0.43

[a] From Peck et al. (1962).

The gas-filled porosity, θ_a, is the single parameter in Equation 1-2 with the most variability. Theoretically, it can be related to the total porosity, soil bulk density, and moisture content. A doubling of the air-filled porosity results in a doubling of the estimated hydrocarbon degradation rate. Gas-filled porosity may be as high as 0.5 to 0.6 in some very dry clays and is zero in saturated soil. To collect soil gas samples, the gas-filled porosity must be sufficient to allow gas flow. Therefore, an in situ respiration test could be conducted at very low gas-filled porosity. At most bioventing sites, θ_a ranges from 0.1 to 0.4. Soil in a core or split spoon sample will be compressed, thereby reducing θ_a. It can be estimated as follows:

$$\theta_a = \theta - \theta_W \qquad \text{(Eq. 1-3)}$$

where:

θ = total porosity (cm^3/cm^3)

θ_W = water-filled porosity (cm3/cm^3)

The total void volume may be estimated as:

$$\theta = 1 - \frac{\rho_k}{\rho_T} \qquad \text{(Eq. 1-4)}$$

where:

ρ_k = soil bulk density (g dry soil/cm3) (from Table 1-7)

ρ_T = soil mineral density (g/cm^3), estimated at 2.65

The water-filled void volume then can be calculated as:

$$\theta = M\,\frac{\rho_k}{\rho_T} \qquad \text{(Eq. 1-5)}$$

where:

M = soil moisture (g moisture/g soil)

Because the water-filled porosity (θ_W) is a difficult parameter to estimate accurately, an assumption is frequently made of 0.2 or 0.3.

Using several assumptions, values for θ_a, ρ_{O_2}, C, and ρ_k can be calculated and substituted into Equation 1-2. Assumptions used for these calculations are:

- Gas-filled porosity (θ_a) of 0.25.
- Soil bulk density (ρ_k) of 1.4 g/cm.
- Oxygen density (ρ_{O_2}) of 1,330 mg/L.
- C, hydrocarbon-to-oxygen ratio of 0.29 from Equation 1-1 for hexane.

The resulting equation is:

$$k_B = \frac{-(k_o)\,(0.25)\,(1{,}330)\,(0.29)\,(0.01)}{1.4} = -0.68\ k_o$$

(Eq. 1-6)

The biodegradation rates measured by the in situ respiration test appear to be representative of those for a full-scale bioventing system. Miller (1990) conducted a 9-month bioventing pilot project at Tyndall AFB at the same time Hinchee et al. (1991a) conducted an in situ respiration test. The oxygen utilization rates (Miller, 1990) measured from nearby active treatment areas were virtually identical to those measured in the in situ respiration test. Oxygen utilization rates greater than 1.0 percent/day are a good indicator that bioventing may be feasible at the site and proceeding to soil gas permeability testing is appropriate. If oxygen utilization rates are less than 1.0 percent/day, yet significant contamination is present, other factors may be involved in limiting biodegradation. In this case, other process variables, as discussed in Section 3.3, should be considered as limiting biodegradation. Identifying these other process variables may require additional soil sampling and analysis. If none of these other process variables can be identified as potentially limiting microbial degradation, alternative technologies may have to be employed for site remediation.

Example 1-6. Results From an in Situ Respiration Test Conducted at Keesler AFB: At the site described in Example 1-1, an in situ respiration test was conducted. After the soil gas survey, three-level monitoring points were installed at each soil gas survey point location because these areas were highly contaminated and were oxygen-limited. Initial soil gas readings were taken at each monitoring point and are shown in Table 1-8. Because all locations were oxygen-limited, a decision was made to inject air at the deepest level of each monitoring point (MP) (K1-MPA-7.0′, K1-MPB-7.0′, K1-MPC-7.0′, and K1-MPD-7′1″).

Table 1-9 contains data collected at each monitoring point during the in situ respiration test. The oxygen utilization rate is determined as the slope of the percent

Table 1-8. Initial Soil Gas Readings at Monitoring Points at AOC A, Keesler AFB, Mississippi

Monitoring Point	Depth (ft)	Oxygen (%)	Carbon Dioxide (%)	TPH (ppmv)
K1-MPA	3.0	0.1	16	>100,000
	5.0	0.4	15	>100,000
	7.0	0.6	15	>100,000
K1-MPB	2.5	0.5	15	>100,000
	4.0	0.5	15	>100,000
	7.0	0.8	15	>100,000
K1-MPC	3.0	0.4	14	28,000
	5.0	0.1	15	30,000
	7.0	0.5	15	29,000
K1-MPD	3.0	0.6	14	45,000
	5.0	0.5	15	54,000
	7′1″	0.5	15	58,000
Background		16.8	4.6	140

Table 1-9. Raw Data From an in Situ Respiration Test at AOC A, Keesler AFB, Mississippi

	K1-MPA-5.0′			K1-MPA-7.0′		
Time (hr)	O_2 (%)	CO_2 (%)	He (%)	O_2 (%)	CO_2 (%)	He (%)
0	20.7	0	1.4	20.5	0	1.4
5	20.6	0	1.6	20.6	0	1.4
10	20.1	0.1	1.4	20.3	0.1	1.4
25	19.0	0	1.75	20.1	0	1.6
37	17.8	0	1.4	19.5	0	1.4
50	16.9	0.6	1.4	18.7	0.2	1.25
75	15.2	1.2	1.6	17.3	1.2	1.6
99	14.0	2.0	1.4	16.3	1.2	1.4
Time (hr)	K1-MPB-5.0′			K1-MPC-7.0′		
0	20.6	0	1.6	20.8	0	1.3
5	20.2	0	1.8	20.5	0.2	1.5
10	19.4	0	14	20.2	0.2	1.4
25	16.9	0	1.6	19.5	0	1.3
37	14.8	0	1.4	18.1	0.6	1.2
50	12.9	1.0	1.4	16.9	1.5	1.2
75	9.9	2.6	1.2	13.9	3.0	1.0
99	8.0	3.0	1.2	11.0	4.0	1.0

O_2 = oxygen.
CO_2 = carbon dioxide.
He = helium.

oxygen versus time curve. Only data beginning with that taken at t = 0 that appear linear with time were used to calculated the slope. A zero-order respiration rate as seen in these data is typical of most sites (Figure 1-7). Calculated oxygen utilization rates and corresponding biodegradation rates for these data are shown in Table 1-10.

Results of this test indicate that this site is an excellent candidate for bioventing.

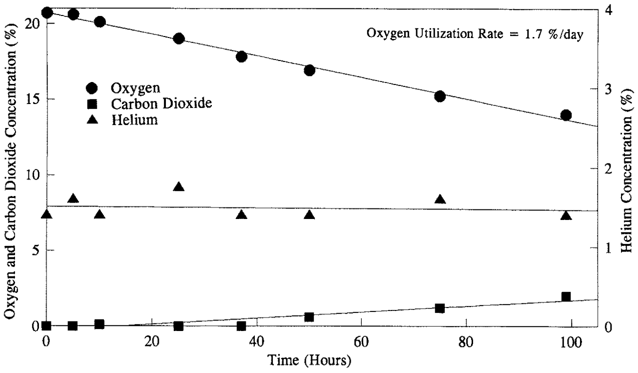

Figure 1-7. In situ respiration test results with linear oxygen concentration versus time at AOC A, Keesler AFB, Mississippi.

Table 1-10. Oxygen Utilization and Carbon Dioxide Production Rates During the in Situ Respiration Test at AOC A, Keesler AFB, Mississippi

Sample Name	Oxygen Utilization Rate (%/hour)	Estimated Biodegradation Rate (mg/kg-day)
K1-MPA-5.0′	0.071	1.16
K1-MPA-7.0′	0.045	0.73
K1-MPB-5.0′	0.13	2.12
K1-MPC-7.0′	0.099	1.62
Background	0.012	0.20

Example 1-6 illustrates calculation of oxygen utilization data that are linear with time. In some instances, however, this relationship is not linear, and only selected data should be used to calculate the oxygen utilization rate. Example 1-7 illustrates calculation of the oxygen utilization rate from nonlinear data.

Example 1-7. Calculation of Oxygen Utilization Rates From Nonlinear Data: Table 1-11 contains sample data from Solid Waste Management Unit (SWMU) 66, Keesler AFB. The oxygen utilization rate is determined as the slope of the percentage of oxygen versus time curve. Only data beginning with that taken at t = 0 that appear linear with time should be used to calculate the slope. A fairly rapid change in oxygen levels was observed at Keesler AFB (Figure 1-8). In this case, the oxygen utilization rate was obtained from the initial linear portion of the respiration curve, which included data from t = 0 to t = 30.5 hours. As shown, after this point, oxygen concentrations dropped below 5 percent and were limiting. The calculated oxygen utilization rate was 11 percent/day.

Table 1-11. Raw Data From an in Situ Respiration Test at SWMU 66, Keesler AFB, Mississippi

Time (Hours)	Oxygen (%)	Carbon Dioxide (%)	Helium (%)
0	20.5	0	1.6
6.3	18.1	.05	1.6
9.3	16.5	1.0	1.6
15	14	2.2	1.8
22	11	3.2	1.5
31	6.8	5.0	1.5
48	3.7	5.1	1.5
57	2.9	5.1	1.5

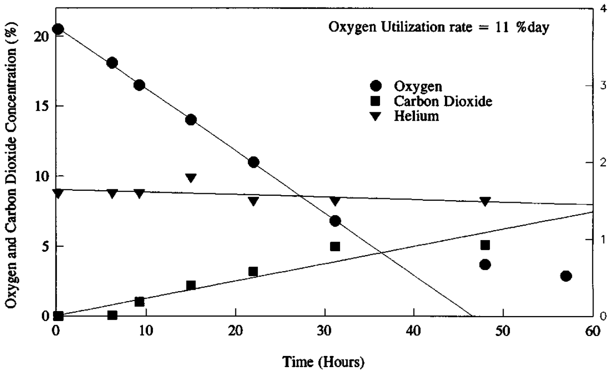

Figure 1-8. In situ respiration test results with nonlinear oxygen concentration versus time at SWMU 66, Keesler AFB, Mississippi.

The helium data collected at a site provide insight into whether observed oxygen utilization rates are caused by microbial utilization or by other effects such as leakage or diffusion. As a rough estimate, diffusion of gas molecules is inversely proportional to the square root of the molecular weight of the gas. Based on the molecular weights of 4 g/mole and 32 g/mole for helium and oxygen, respectively, helium diffuses about 2.8 times faster than oxygen. Thus, although helium is a conservative tracer, its concentration should decrease with time. As a general rule of thumb, any in situ respiration test in which the rate of helium loss is less than the oxygen loss rate should be considered an acceptable test. If the helium loss rate is greater than the oxygen loss rate, disregard the test from that monitoring point. The helium loss rate is not used to correct the oxygen utilization rate.

Example 1-8. Evaluation of Helium Loss During an in Situ Respiration Test: Figures 1-9 and 1-10 show helium data for two test wells. The helium concentration at monitoring point S1 at Tinker AFB (Figure 1-9), initially at 1.5 percent, dropped to 1.1 percent after 108 hours (a fractional loss of approximately 0.25); this represented an acceptable concentration drop. In contrast, for Kenai K3 (Figure 1-10), the change in helium was rapid (a fractional drop of about 0.8 in 7 hours), indicating possible short circuiting at this monitoring point. This suggested that the data from this monitoring point were unreliable, so these data were not used in calculating degradation rates.

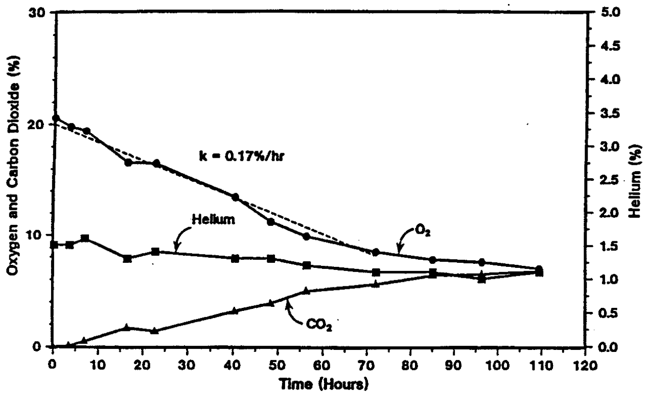

Figure 1-9. In situ respiration test results with acceptable data based on the helium concentration for monitoring point S1, Tinker AFB, Oklahoma.

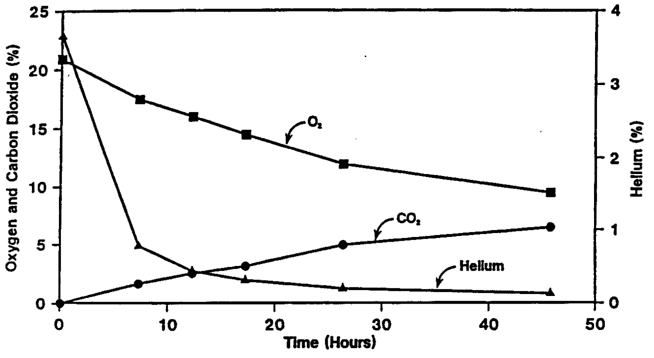

Figure 1-10. In situ respiration test results with unacceptable data based on the helium concentration for monitoring point K3, Kenai, Alaska.

1.4.3 Factors Affecting Observed in Situ Biodegradation Rates

Because in situ biodegradation rates are measured indirectly through measurements of soil gas oxygen and carbon dioxide concentrations, abiotic processes that affect oxygen and carbon dioxide concentration also affect measured biodegradation rates. The factors that may most influence soil gas oxygen and carbon dioxide concentrations are soil pH, soil alkalinity, and iron content. In addition, any environmental parameter that may affect microbial activity also may affect observed oxygen utilization rates. Soil temperature often is a significant factor at bioventing sites.

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

In the case of the higher pH and higher alkalinity soils at Fallon NAS and Eielson AFB, little or no gaseous carbon dioxide production was measured (Hinchee et al., 1991b; Leeson et al., 1995). This may be the result of the formation of carbonates from the gaseous evolution of carbon dioxide produced by biodegradation at these sites. Van Eyk and Vreeken (1988) encountered a similar phenomenon in their attempt to use carbon dioxide evolution to quantify biodegradation associated with soil venting.

Iron is a nutrient required for microbial growth, but the iron also may react with oxygen to form iron oxides. Theoretically, if a significant amount of iron oxidation were to occur, the observed oxygen utilization rate would reflect both iron oxidation and microbial activity. Therefore, calculated biodegradation rates would be an overestimate of actual biodegradation rates. In data collected from the Bioventing Initiative study, however, iron concentrations have varied greatly, with concentrations from less than 100 mg/kg to greater than 100,000 mg/kg, with no apparent impact on oxygen utilization rates. Iron impact on oxygen utilization rates has been observed at only one site with very high iron concentrations—on the Marine Base at Kaneohe, Hawaii, where soil iron concentrations are in the 100,000 mg/kg range.

An important consideration is whether the respiration rate was measured at the time of year when microbial rates were at their maximum (summer) or if it was measured when activity was low (winter). Investigations at many sites have shown that rates can vary by as much as an order of magnitude between peak periods. For design of oxygen delivery systems, respiration rates should be measure during the peak season, typically during late summer.

If oxygen utilization rates were determined during periods of low activity, it is necessary to adjust the rates to the maximum level before making size calculations. The van't Hoff-Arrhenius equation can be used to predict oxygen utilization rates given an initial rate and temperature.[8] The activation energy, E_a, must be known for the site. Alternatively, E_a found from another site can be used, recognizing the temperature-adjusted rate is only a rough estimate. The following example illustrates a typical adjustment.

Example 1-9. Temperature Adjustment of Oxygen Utilization Rate: The oxygen utilization rate was measured in January at a site in Cheyenne, Wyoming. The rate was determined to be 0.75 percent/day (0.031 percent/hour). The temperature in the soil was measured at 4°C. Previous temperature measurements at the site have indicated that soil temperatures in August average approximately 24°C (i.e., 20°C higher than the temperature measured during January). The temperature adjustment to the rate for sizing calculations is as follows:

Using the van't Hoff-Arrhenius equation (Metcalf & Eddy, 1979):

$$\frac{dk}{dT} = \frac{E_a}{RT_2}$$

Integration of this equation between the limits T_1 (277°K) and T_2 (297°K) gives:

$$\ln \frac{k_T}{k_o} = \frac{E_a\,(T_2 - T_1)}{RT_1T_2}$$

where:

k_T = temperature-corrected oxygen utilization rate (% O2/day)

k_o = baseline reaction rate = 0.75%/day

E_a = activation energy[9] = 13.4 kcal/mole

R = gas constant = 1.987 cal/°K-mole

T_1 = absolute temperature for k_o = 277°K

T_2 = absolute temperature for k_T = 297°K

$$k_T = \left(0.75\,\frac{\%}{\text{day}}\right) e^{\left[\frac{(13{,}400\ \text{cal/mole})\ (297°\text{K} - 277°\text{K})}{(1.987\ \frac{\text{cal}}{°\text{K–mole}})\ (297°\text{K})(277°\text{K})}\right]}$$

$$k_T = 3.9\,\frac{\%}{\text{day}}$$

As seen in this calculation, the site would require approximately five times greater oxygen delivery rate in the summer.

1.5 Soil Gas Permeability and Radius of Influence

In situ respiration rates may be used to calculate the required air flow rate to satisfy oxygen demand at a given site;[10] however, determining the distance air can physically be moved also is necessary. An estimate of the soil's permeability to fluid flow (k) and the radius of influence (R_I) of venting wells are both important elements of a full-scale bioventing design. Onsite testing provides the most accurate estimate of soil gas permeability. Onsite testing also can 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, and to ensure that the entire site receives a supply of oxygen-rich air to sustain in situ biodegradation.

Soil gas permeability, or intrinsic permeability, can be defined as a soil's capacity for fluid flow and varies according to grain size, soil uniformity, porosity, and moisture content. The value of k is a physical property of the soil; k does not change with different extraction/injection rates or different pressure levels.

Soil gas permeability is generally expressed in the units cm^2 or darcy (1 darcy = 1×10^{-8} cm^2). Like hydraulic conductivity, soil gas permeability may vary by more than an order of magnitude on the same site because of soil variability. Table 1-12 illustrates the range of typical k values to be expected with different uniform soil types. Actual soils contain a mixture of grain sizes, which generally increases the observed darcy values based on pilot testing.

Table 1-12. Soil Gas Permeability Values (Johnson et al., 1990)

Soil Type	k in Darcy
Coarse sand	100 to 1,000
Medium sand	1 to 100
Fine sand	0.1 to 1.0
Silts/clay	<0.1

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[8] See Volume I for a discussion of the effect of temperature on microbial activity.

[9] Calculated from a different field site. See Example 3-2 in Volume I for a description of the calculation of the activation energy.

[10] See Section 2.2 for a presentation of the calculation of required air flow rates.

Several field methods have been developed for determining soil gas permeability (EPA, 1991b). The most favored field test method probably is the modified field drawdown method developed by Paul Johnson at Arizona State University and former associates at the Shell Development Company. This method involves the injection or extraction of air at a constant rate from a single venting well while measuring the pressure/vacuum changes over time at several monitoring points in the soil away from the venting well.[11]

The field drawdown method is based on Darcy's law and equations for steady-state radial flow to or from a vent well. A full mathematical development of this method and supporting calculations are provided by Johnson et al. (1990). Johnson developed the HyperVentilate computer program to store field data and to compute soil gas permeability. This or other commercially available programs can be used to speed the calculation and data presentation process.

Two solution methods may be used for soil gas permeability as described in Johnson et al. (1990). The first solution is based on carefully measuring the dynamic response of the soil to a constant injection or extraction rate. The second solution for soil gas permeability is based on steady-state conditions and the measurement or estimation of the radius of influence at steady state. Whenever possible, field data should be collected to support both solution methods because one or both of the solution methods may be appropriate, depending on site-specific conditions. An example procedure for conducting a soil gas permeability test is provided in Appendix C.

1.5.1 Radius of Influence Determination Based on Pressure Measurements

At a bioventing site, the radius of influence is defined in two ways, as the oxygen radius of influence or the pressure radius of influence. The oxygen radius of influence is defined as the maximum distance from the air extraction or injection well where a sufficient supply of oxygen for microbial respiration can be delivered. The pressure radius of influence is the maximum distance from the air extraction or injection well where vacuum or pressure (soil gas movement) occurs. Under heterogeneous conditions, the pressure radius of influence is theoretically infinite; for practical purposes, however, it usually is considered to be the maximum extent to which pressure changes can be measured.

The oxygen and pressure radius of influence is a function of soil properties but also is dependent on the configuration of the venting well and extraction or injection flow rates and is altered by soil stratification. The oxygen radius of influence also is dependent on microbial oxygen utilization rates. On sites with shallow contamination, the oxygen and pressure radius of influence also may be increased by impermeable surface barriers such as asphalt or concrete. These paved surfaces may or may not act as vapor barriers. Without a tight seal to the native soil surface,[12] the pavement will not significantly affect soil gas flow.

At a bioventing site, the oxygen radius of influence is the true radius of influence for system design. A connection exists between the pressure radius of influence and the oxygen radius of influence; however, many variables exist that are not fully understood. Empirically, during a soil gas permeability test, an increase in oxygen concentration has been found at contaminated sites wherever pressure changes are measured. Also, the pressure radius of influence has been found to be a conservative measure of the oxygen radius of influence. The oxygen radius of influence may be directly determined by measuring the distance from the vent well at which a change in oxygen concentration can be detected. Several days or weeks may pass, however, before equilibrium is reached and an accurate oxygen radius of influence is measured.

In addition, if microbial acclimation occurs, microbial activity may increase, effectively reducing the oxygen radius of influence because of increased oxygen consumption. Therefore, the best approach is to measure the oxygen radius of influence at times of peak microbial activity. Alternatively, the pressure radius of influence may be determined very quickly, generally within 2 hours to 4 hours. Therefore, the pressure radius of influence typically is used to design bioventing systems.

The pressure radius of influence should be determined at three different flow rates, with a 1-hour to 2-hour test per flow rate during the permeability test. Determining the radius of influence at different flow rates allows for more accurate blower sizing.[13] Recommended flow rates for the permeability test are 0.5 cfm, 1.5 cfm, and 3 cfm (14 L/min, 42 L/min, and 85 L/min) per ft (0.3 m) of well screen.

The pressure radius of influence may be estimated by determining pressure change versus distance from the vent well. The log of the pressure is plotted versus the distance from the vent well. The radius of influence is that distance at which the curve intersects a pressure of 0.1″H_2O (25 Pa). This value was determined empirically from Bioventing Initiative sites. Example 1-10 illustrates calculating the radius of influence in this manner.

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[11] See Appendix B for recommended specifications and manufacturers for the soil gas permeability testing equipment.

[12] In the authors' experience, this seal does not occur at most sites.

[13] See Section 2.4 for a discussion of blower sizing.

Example 1-10. Calculation of the Radius of Influence Based on Pressure Measurements: Soil gas permeability results from the Saddle Tank Farm Site at Galena AFS, Alaska, are shown in Figure 1-11 with the log of the steady-state pressure response at each monitoring point plotted versus the distance from the vent well. The radius of influence is taken to be the intersection of the resulting slope of the curve at a pressure of 0.1"H_2O (25 Pa). Therefore, in this instance, the pressure radius of influence would be estimated at 92 ft (28 m).

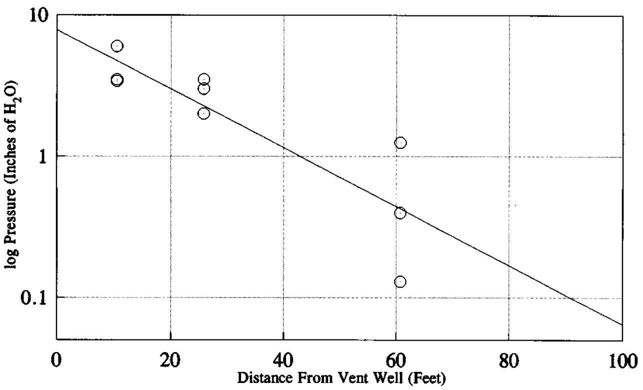

Figure 1-11. Determination of radius of influence at the Saddle Tank Farm, Galena AFS, Alaska.

The estimated radius of influence actually is an estimate of the radius in which measurable soil gas pressures are affected and does not always equate to gas flow. In highly permeable gravel, for example, significant gas flow can occur well beyond the measurable radius of influence. On the other hand, in a low-permeability clay, a small pressure gradient may not result in significant gas flow.

1.5.2 Interpretation of Soil Gas Permeability Testing Results

The technology of bioventing has not advanced far enough to provide firm quantitative criteria for determining the applicability of bioventing based solely on values of soil permeability or the radius of influence. In general, the soil permeability must be sufficiently high to allow movement of oxygen in a reasonable timeframe (1 to 10 days) from either the vent well, in the case of injection, or the atmosphere or uncontaminated soils, in the case of extraction. If such a flow rate cannot be achieved, oxygen cannot be supplied at a rate to match its demand. Closer vent well spacing or high injection/extraction rates may be required.

If either the soil gas permeability or the radius of influence is high (greater than 0.01 darcy or a R_I greater than the screened interval of the vent well), this is a good indicator that bioventing may be feasible at the site and proceeding to soil sampling and full-scale design is appropriate. If either the soil gas permeability or the radius of influence is low (less than 0.01 darcy or a R_I less than the screened interval of the vent well), this may indicate that bioventing is not feasible. This situation necessitates an evaluation of the cost-effectiveness of bioventing over other alternative technologies for site remediation. The cost involved in installing a bioventing system at a low-permeability site is driven primarily by the necessity of installing more vent wells, using a blower with a higher delivery pressure, or installing horizontal wells.

Chapter 2
System Design

The design of a bioventing system is based upon the results of site characterization and pilot testing efforts described in Chapter 1. The objective is to design a system that results in aeration of the contaminated soils with little or no volatilization. Aeration may be accomplished through air injection, gas extraction, or a combination of the two. Soil vacuum extraction (SVE) (also known as soil venting, soil gas extraction, or vacuum vapor extraction) is a related technology in which soil gas is extracted to remove contaminants by volatilization. In contrast, bioventing is designed to minimize volatilization and optimize biodegradation. As a result, bioventing typically uses much lower air flow rates and often does not involve air extraction.

The basic steps involved in designing a bioventing system are as follows:

- Determine required air flow system (injection, extraction, or both [Section 2.1]).
- Determine required air flow rates (Section 2.2).
- Determine the working radius of influence.
- Determine well spacing (Section 2.3).
- Provide detailed design of blower, vent wells, and piping (Section 2.4).
- Determine vent well requirements (Section 2.5).
- Determine monitoring point requirements (Section 2.6).

2.1 Determination of Air Flow System

In general, if safe and feasible, air injection is the preferred configuration for full-scale bioventing systems. If properly designed, air injection results in minimal discharge of volatile organics to the atmosphere and is less expensive to operate and maintain than air extraction systems.

Under some circumstances, the use of soil gas extraction systems may need to be incorporated into an air injection system design. For example, whenever the radius of influence of a vent well reaches basements, utility corridors, or occupied surface structures, an air extraction system may be used to reduce the risk of moving gases into these areas. This precaution prevents the accumulation of explosive or toxic vapors in these structures.

2.1.1 Air Injection

Air injection involves the introduction of air under pressure into the contaminated zone. If 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 as illustrated in Figure 2-1. Given adequate oxygen, the volatilized hydrocarbons will biodegrade in these surrounding uncontaminated soils, increasing the fraction of contaminants biodegraded compared with an air extraction configuration. This concept is illustrated in Example 2-1.

Example 2-1. Biodegradation of Petroleum Hydrocarbons in the Uncontaminated and Contaminated Regions at Site 280, Hill AFB: At this site, high vapor-phase TPH concentrations were detected within a radius of approximately 50 ft (15 m) from the injection well. TPH concentrations decreased with increasing distance from the well. Likewise, in situ respiration rates were observed to decrease with increasing distance from the injection well (Figure 2-2). Calculations were made to compare total TPH mass degraded in each region based on these in situ respiration rates. These results, shown in Figure 2-3, illustrate that even though relatively low in situ respiration rates were measured at monitoring points located far from the injection well (220 ft [67 m]), in fact, the majority of the contaminant degradation was occurring in this area. These results illustrate the availability of vapor-phase hydrocarbons for biodegradation and the significant contribution an expanded bioreactor can have on contaminant removal.

Miller (1990) found at the Tyndall AFB site that hydrocarbon vapors biodegrade at a rate approximately equal to one-third the rate observed in contaminated soils. Kampbell (1993) found that the vapor-phase biodegradation in an air injection system was greatest in shallow root zone soils. The concept is analogous to an in situ biofilter. In general, air can be injected at flow rates low

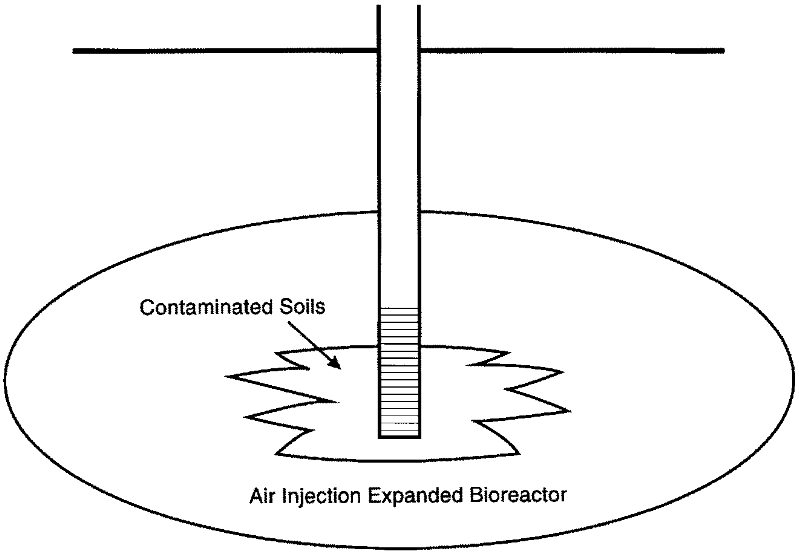

Figure 2-1. Expanded bioreactor created during air injection.

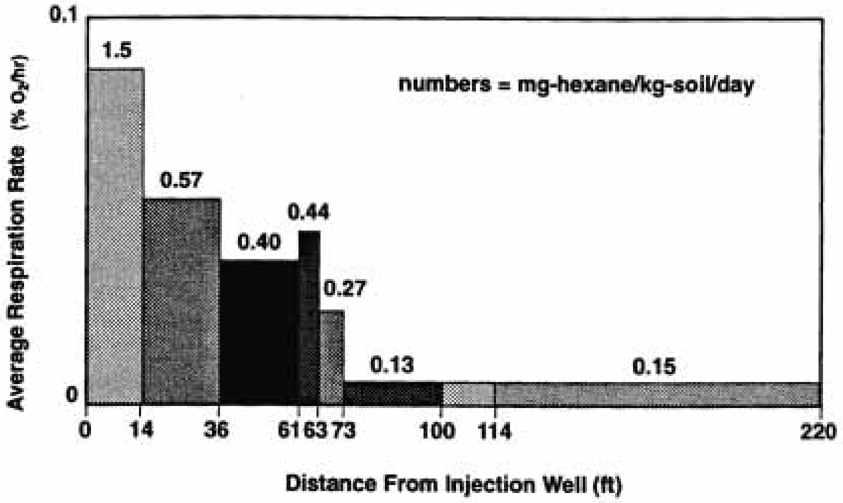

Figure 2-2. Oxygen utilization rates, averaged over depth, versus distance from the injection well at Site 280, Hill AFB, Utah.

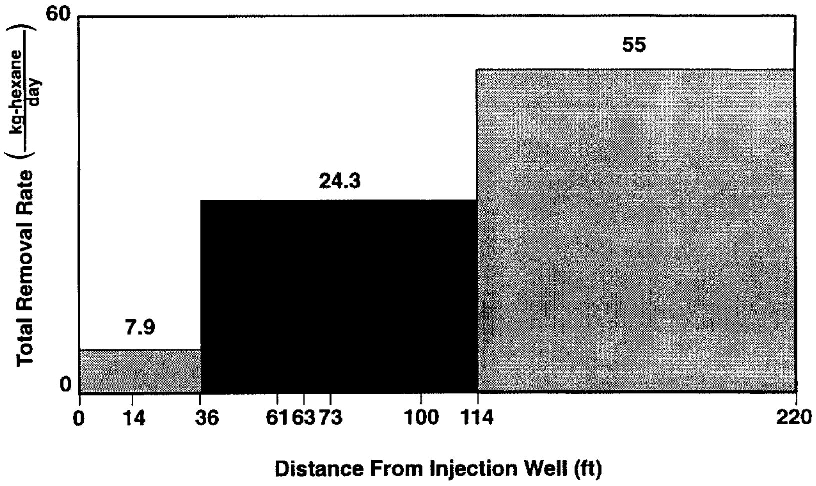

Figure 2-3. Mass of TPH degraded versus distance from the injection well at Site 280, Hill AFB, Utah.

enough to avoid surface emissions. As the air injection rate increases, hydrocarbon volatilization increases (Figure 2-4). Therefore, the objective is to inject sufficient air to meet oxygen demand for biodegradation but not to cause emissions to the atmosphere. 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).[1]

In addition to creating an expanded bioreactor, air injection could potentially expose a significant portion of capillary fringe contaminated soil to treatment via water table depression. As air is injected into the vadose zone, a positive pressure is created, resulting in depression of the water table. Figure 2-5 illustrates the water table depression observed at Site 20, Eielson AFB, Alaska. This water table depression has important implications. At many sites, the capillary fringe is highly contaminated, and lowering the water table allows for more effective treatment of the capillary fringe. In addition, this dewatering effect frequently results in an increased radius of influence and greater soil gas permeability.

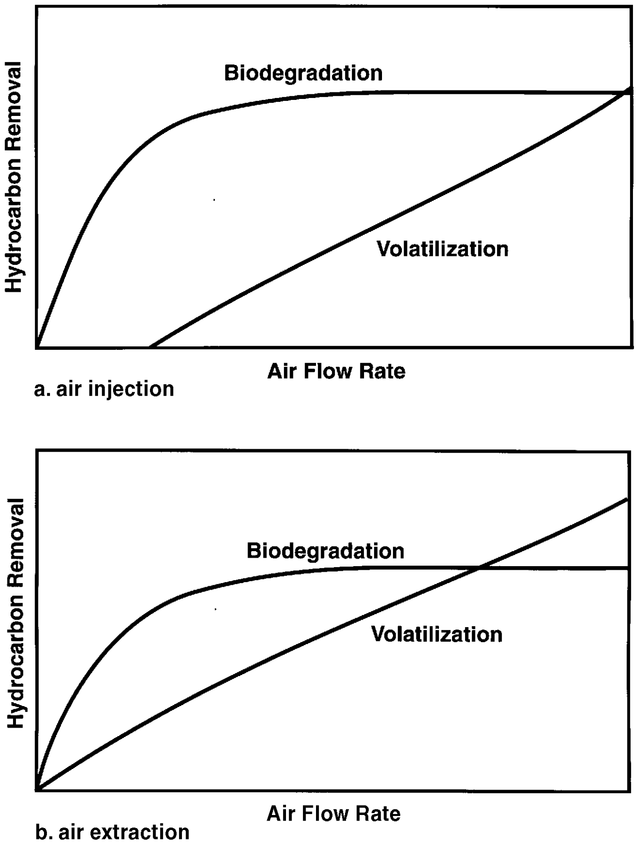

Figure 2-4. Hydrocarbon volatilization and biodegradation rates as a function of air flow rate.

A schematic diagram of a basic air injection system is illustrated in Figure 2-6. The system is relatively simple, involving a blower or compressor and a distribution system. Explosion-proof blowers are recommended for safety. Properly designed and operated injection systems do not produce significant air emissions or require aboveground vapor phase treatment.

2.1.2 Air Extraction

Air injection is the preferred bioventing configuration; however, air extraction may be necessary at sites where movement of vapors into subsurface structures or air emissions is difficult to control. If a building or other structure is located within the radius of influence of a site, or if the site is near a property boundary beyond which hydrocarbon vapors cannot be pushed, air extraction may be considered. A significant disadvantage of the air extraction configuration is that it limits biodegradation to the contaminated soil volume because vapors do not move outward, creating an expanded bioreactor. The result is less biodegradation and more volatilization. In general, increasing extraction rates increase volatilization and biodegradation rates until the site becomes aerated, above which the rate of biodegradation no

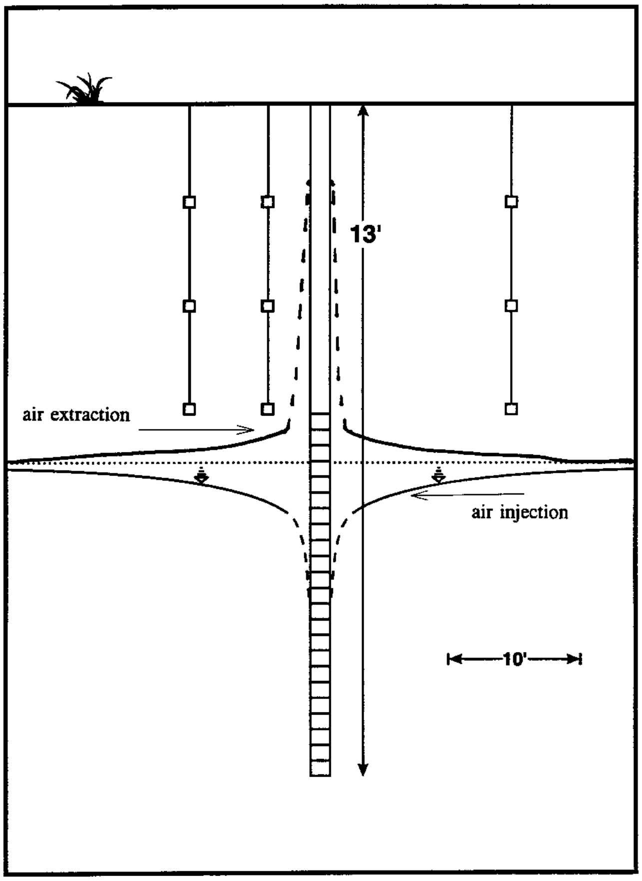

Figure 2-5. Water table depression during air injection and air extraction.

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[1] Reisinger, J. 1994. Personal communication between J. Reisinger, IST, Inc., Atlanta, Georgia, and Battelle Memorial Institute, Columbus, Ohio.

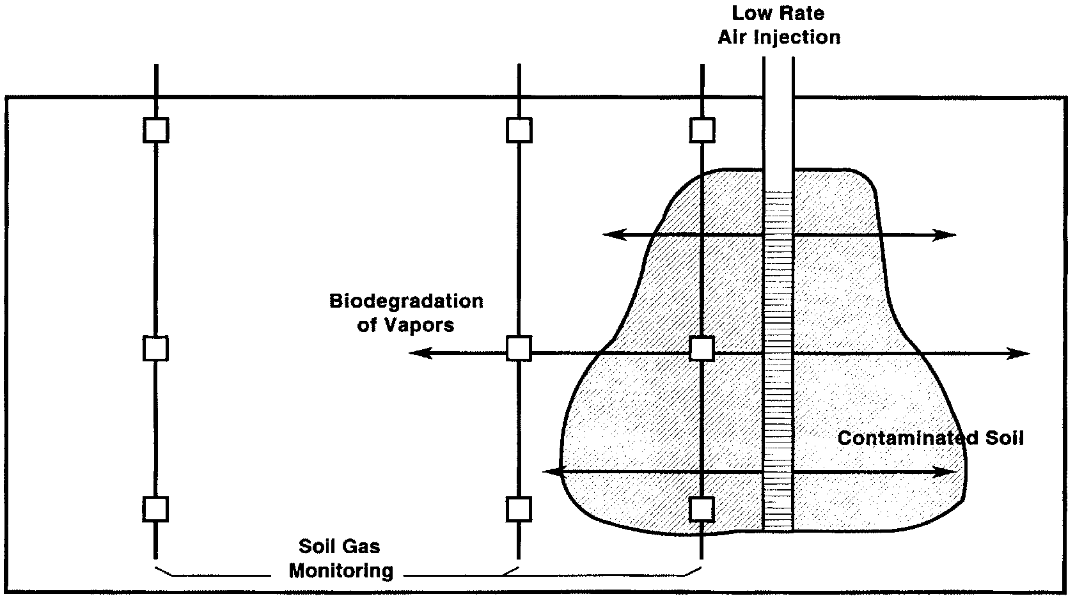

Figure 2-6. Air injection configuration for a bioventing system.

longer increases. Volatilization generally continues to increase with increasing extraction rates until the contaminated soil system becomes diffusion limited. The optimal air flow rate for injection and extraction is the minimum required to satisfy oxygen demand. Extraction systems result in some volatilization regardless of the extraction rate. Figure 2-4 illustrates this concept. The relative removal attributed to biodegradation and volatilization is quite variable and site dependent. At a JP-4 jet fuel contaminated site at Tyndall AFB, Miller et al. (1991) found that at the optimal air injection level it was possible to achieve approximately 85 percent of removal due to biodegradation at the optimal flow rate.

Air extraction creates a partial vacuum in the soil, resulting in a water table and capillary fringe rise or upwelling. The soil venting literature has illustrated this phenomenon (Johnson et al., 1990). Because the bulk of contamination is often several inches or feet above or below the water table (smear zone), this upconing can saturate much of the contaminated soil and reduce treatment efficiency. The upconing also increases soil moisture in the capillary fringe and thus reduces soil gas permeability and radius of influence.

An example of this phenomenon was observed at Eielson AFB. An extraction air permeability test was conducted at Eielson AFB to observe the effect of the bioventing configuration on the site air permeability and well radius of influence. Table 2-1 compares the results of extraction and injection tests at Site 20, Eielson AFB. The permeability (k) calculated for the extraction test was 0.27 darcy, approximately one-half the result for the air injection test. The radius of influence observed at the 6-ft monitoring depth also was reduced approximately one-third to 42 ft (13 m) (Figure 2-7). This reduction in permeability and radius of influence was a result of the water table rising illustrated in Figure 2-5.

Table 2-1. Permeability and Radius of Influence Values at Eielson AFB, Alaska: Injection and Extraction Mode

	Permeability (darcy)		Air Radius of Influence (ft)	
Depth (ft)	Injection	Extraction	Injection	Extraction
2	NR	NR	<7.0	<6.0
4	0.53	0.27	45	34
6	0.56	0.27	68	42

NR = No response.

Figure 2-8 is a schematic of a basic air extraction system. In contrast to an injection system, an extraction system usually requires an explosion-proof blower with explosion-proof wiring. Extracted soil gas typically contains moisture at or near saturation, and a knockout (air/water separator) usually is required to collect condensate, which must be treated or disposed of. Also, during winter months in regions with sustained temperatures below freezing, insulation and/or heat tape may be required to maintain piping at temperatures above freezing to avoid clogged pipes.

Air extraction systems usually result in point source emissions that may require permitting and treatment. Air treatment affects remediation costs significantly. Appendix D contains information on options for off-gas treatment.

Currently, only six sites out of 125 Bioventing Initiative sites use air extraction as a method for oxygenation. Two of the sites (Capehart Service Station, McClellan AFB, and BX Service Station, Patrick AFB) operated in

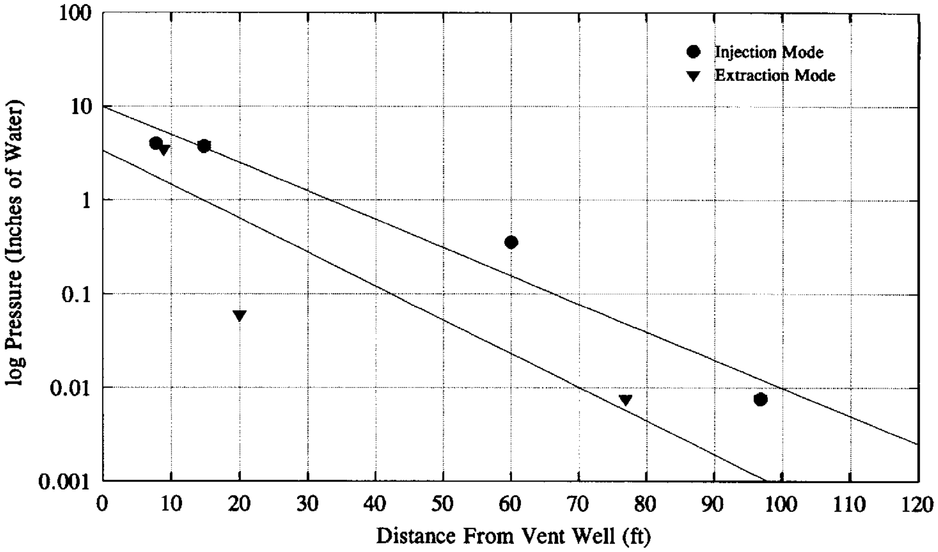

Figure 2-7. Radius of influence during air injection and extraction in the control test plot at a depth of 6 ft at Site 20, Eielson AFB, Alaska.

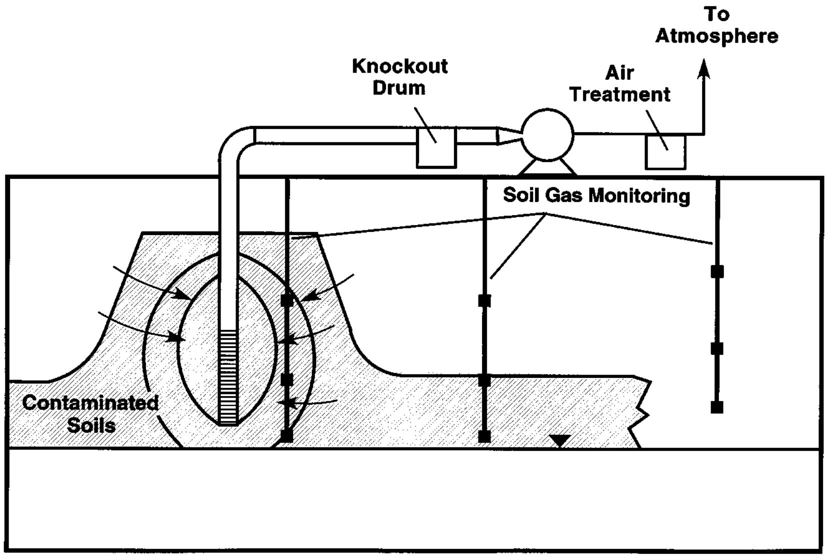

Figure 2-8. Schematic of a basic air extraction system.

extraction mode for 60 to 120 days, at which time the system was reconfigured for air injection because vapor concentrations had significantly decreased. At Patrick AFB, initial vapor concentrations of TPH were as high as 27,000 ppmv (Figure 2-9). After approximately 75 days of operation, concentrations decreased to 1,600 ppmv and the bioventing system was reconfigured for injection (Downey, 1994). The Base Service Station at Vandenberg AFB contained high concentrations of more volatile components of gasoline and is an active service station. As such, the possibility of vapor migration into the service station was possible. This bioventing system was operated in an extraction configuration in two phases (Downey et al., 1994a). During Phase I, extracted soil gas was passed through a PADRE vapor treatment system, where high concentrations of volatiles were adsorbed and condensed to liquid fuel. The treated soil gas was then recirculated through the soil using air injection, biofilter trenches located along the perimeter of the site. Phase II was initiated when TVH concentrations decreased to less than 1,000 ppmv. At this time, the PADRE system was taken off line, and the extracted soil gas was reinjected directly into the biofilter trenches.

2.1.3 Determining Use of Injection Versus Extraction

Safety considerations usually drive the selection of injection versus extraction systems. Air injection should not be used unless a system can be designed that does

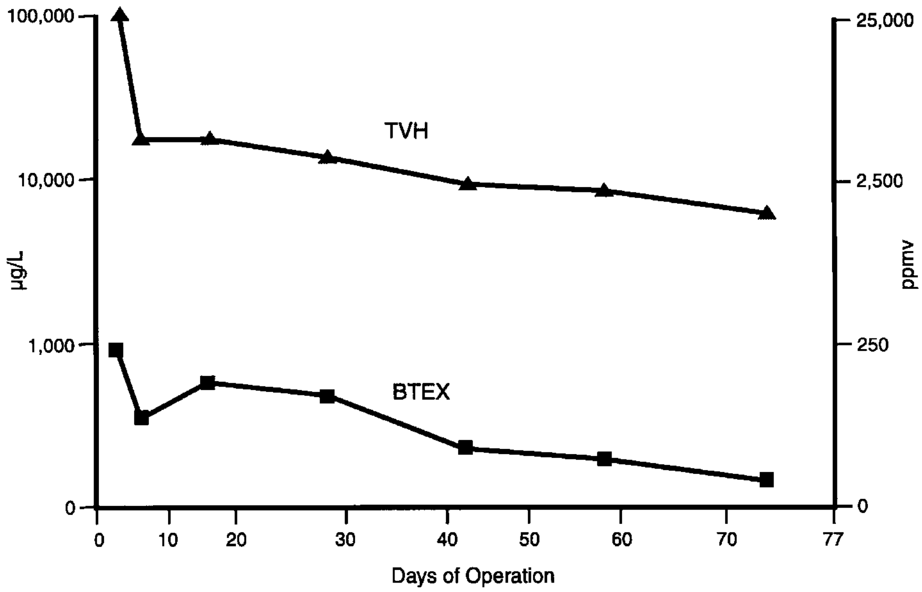

Figure 2-9. Extracted BTEX and TPH soil gas concentrations at Patrick AFB, Florida.

not push hazardous vapors into structures. Table 2-2 summarizes some of the considerations that affect the decision.

Numerous options are available that may allow air injection at sites with structures at risk or with property boundaries nearby (Phelps, 1995). These options include monitoring the atmosphere in the structure to verify that no contaminants enter using air extraction coupled with reinjection to protect the building (Figure 2-10), or using subslab depressurization.

2.1.4 Design of Air Flow To Protect Structures

Subslab depressurization can be used to protect structures while still allowing for air injection to provide optimal oxygenation. Subslab depressurization involves extracting air within or around the perimeter of a building during simultaneous air injection. Vapors extracted from beneath the building may be released to the atmosphere, treated then released, or reinjected into the subsurface for further biotreatment. A schematic of such a system is shown in Figure 2-11.

At AOC A, Keesler AFB, Mississippi, a subslab depressurization system is currently in operation as part of the Bioventing Initiative. A schematic of the site is shown in Figure 2-12. Soil vapor is continually withdrawn from air extraction wells located around the perimeter of the building and reinjected into the vent wells. Makeup air is added to the injection gas to provide sufficient oxygen to aerate the site. No vapor migration into the building has been detected at this site, and the site soils are well oxygenated.

Table 2-2. Air Injection Versus Extraction Considerations

Favor Injection	Favor Extraction
Low vapor pressure contaminants	High vapor pressure contaminants
Deep contamination	Surface emissions
Low permeability soils	Structures/property boundaries within the radius of influence
Significant distance from structures/property boundaries	

At Site 48, Eielson AFB, Alaska, an actively used utilidor runs through the site. The potential for migration of vapors into the utilidor was high. To eliminate the migration of vapors into this structure, a horizontal perforated pipe was installed next to the utilidor. A vertical extraction well was connected to the horizontal pipe to extract gas from along the utilidor for vapor control. The extracted soil gas was then reinjected into a contaminated area at the site (Figure 2-13).

2.2 Determining Required Air Flow Rates

The flow rate required to operate the bioventing system is dependent on the oxygen demand of the indigenous microorganisms. This is best determined from maximum oxygen utilization rates measured during an in situ respiration test. Equation 2-1 is used to estimate the required air flow rate:

$$Q = \frac{k_o \, V \, \theta_a}{(20.9\% - 5\%) \times 60 \, \frac{\text{min}}{\text{hr}}} \qquad \text{(Eq. 2-1)}$$

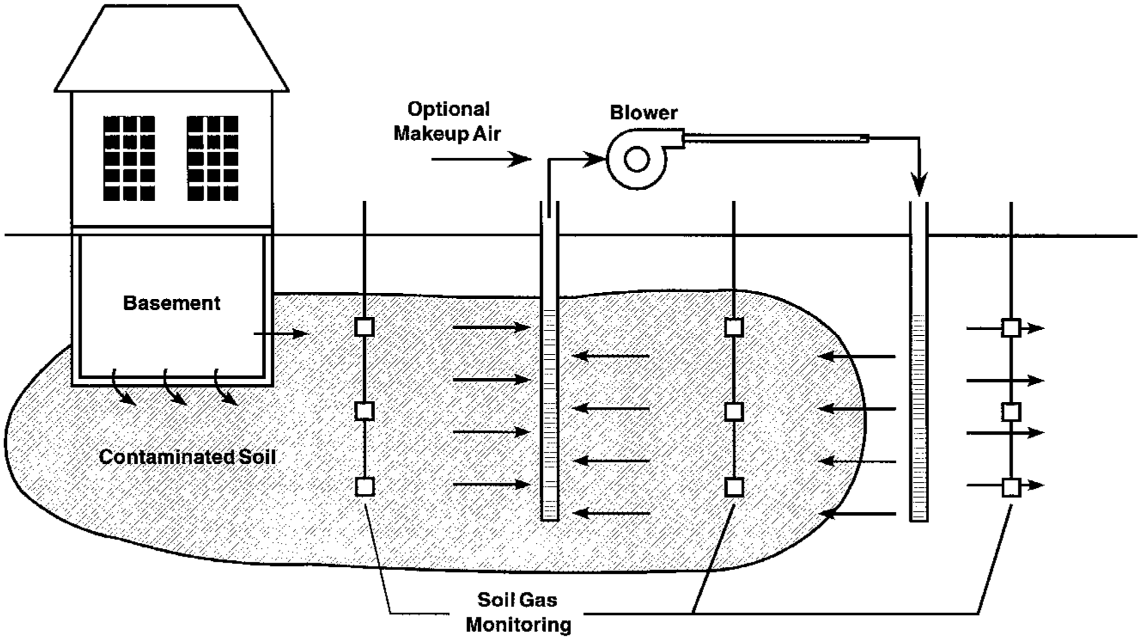

Figure 2-10. Schematic of an air injection system with reinjection of extracted soil gas.

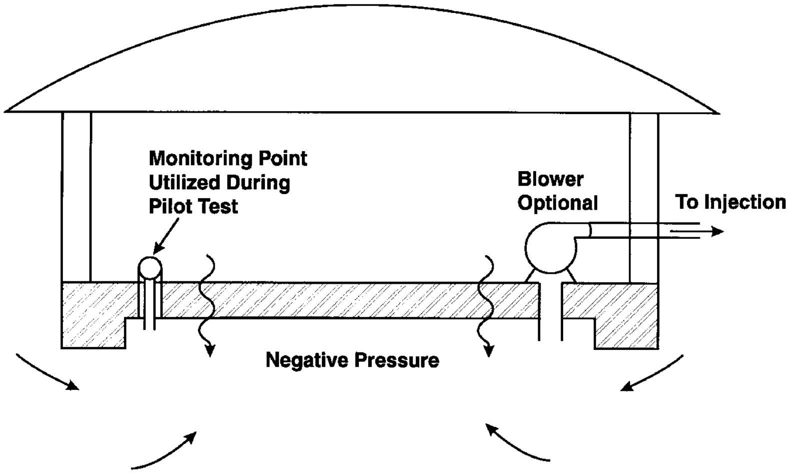

Figure 2-11. Schematic of subslab depressurization.

where:

Q = flow rate (ft^3/min)
k_0 = oxygen utilization rate (%/hr)
V = volume of contaminated soil (ft^3)
θ_a = gas-filled porosity (fraction, i.e., 0.2 or 0.3)

Example 2-2 illustrates the use of this calculation.

Example 2-2. Determination of Required Air Flow Rate: Given a volume of contaminated soil of approximately 170,000 ft^3 (4,760 m^3), an air-filled void volume (θ_a) at this site of 0.36,[2] and an oxygen utilization rate of 0.25 percent/hr, the flow rate is calculated as follows:

$$Q = \frac{(0.25\%/\text{hr})(170{,}000\ \text{ft}^3)(0.36)}{(20.9\% - 5\%) \times 60\ \text{min/hr}} \qquad \text{(Eq. 2-2)}$$

Therefore, the required flow rate is approximately 16 cfm (453 L/min).

The flow rate calculated and used must be confirmed during operation of the bioventing system by monitoring soil gas composition to ensure adequate oxygen levels at all locations.

Data from numerous sites contaminated with various types and mixtures of contaminants have shown that microbial activity is not oxygen limited above oxygen concentrations of approximately 1 percent to 2 percent. To ensure the presence of adequate oxygen levels in the

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[2] See Section 1.4.2 on using moisture content to estimate this parameter.

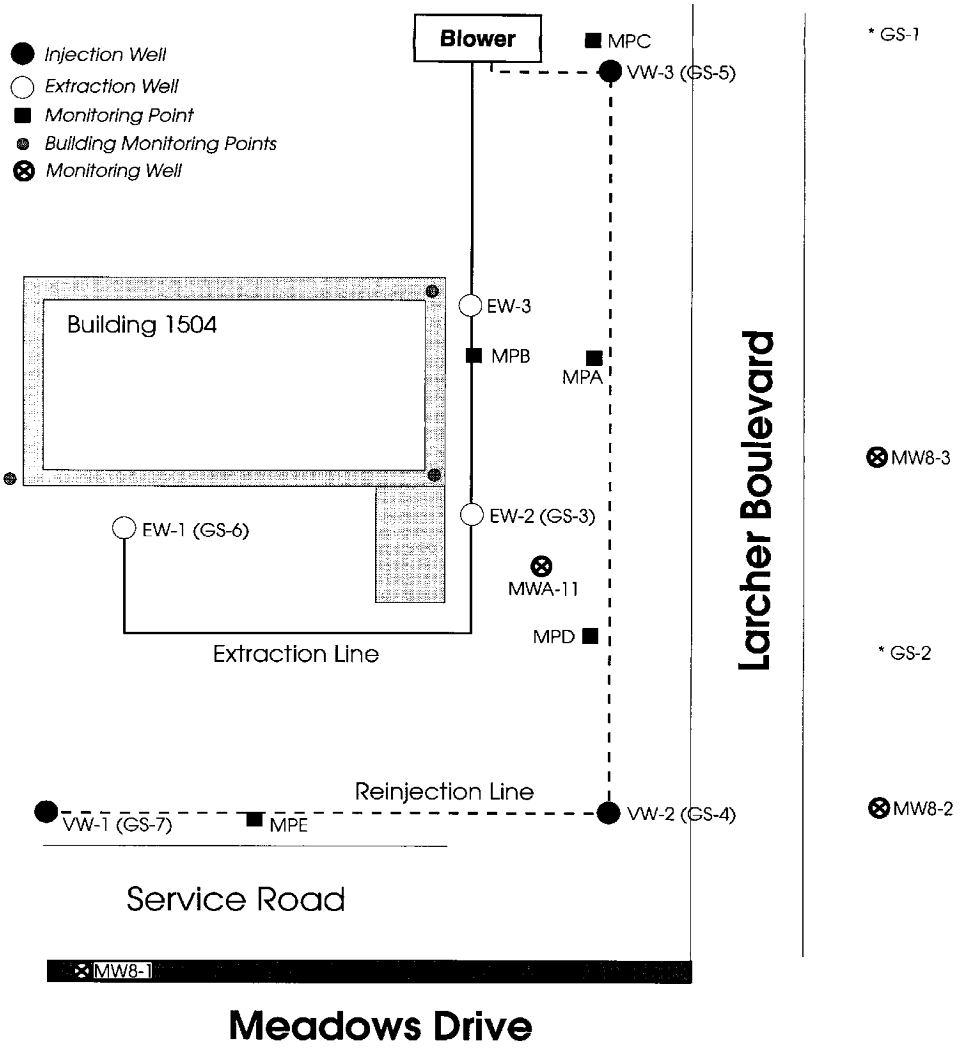


Figure 2-12. Schematic of the extraction with reinjection system at AOC A, Keesler AFB, Mississippi.

entire treatment cell, a minimum level of 5 percent should be maintained.

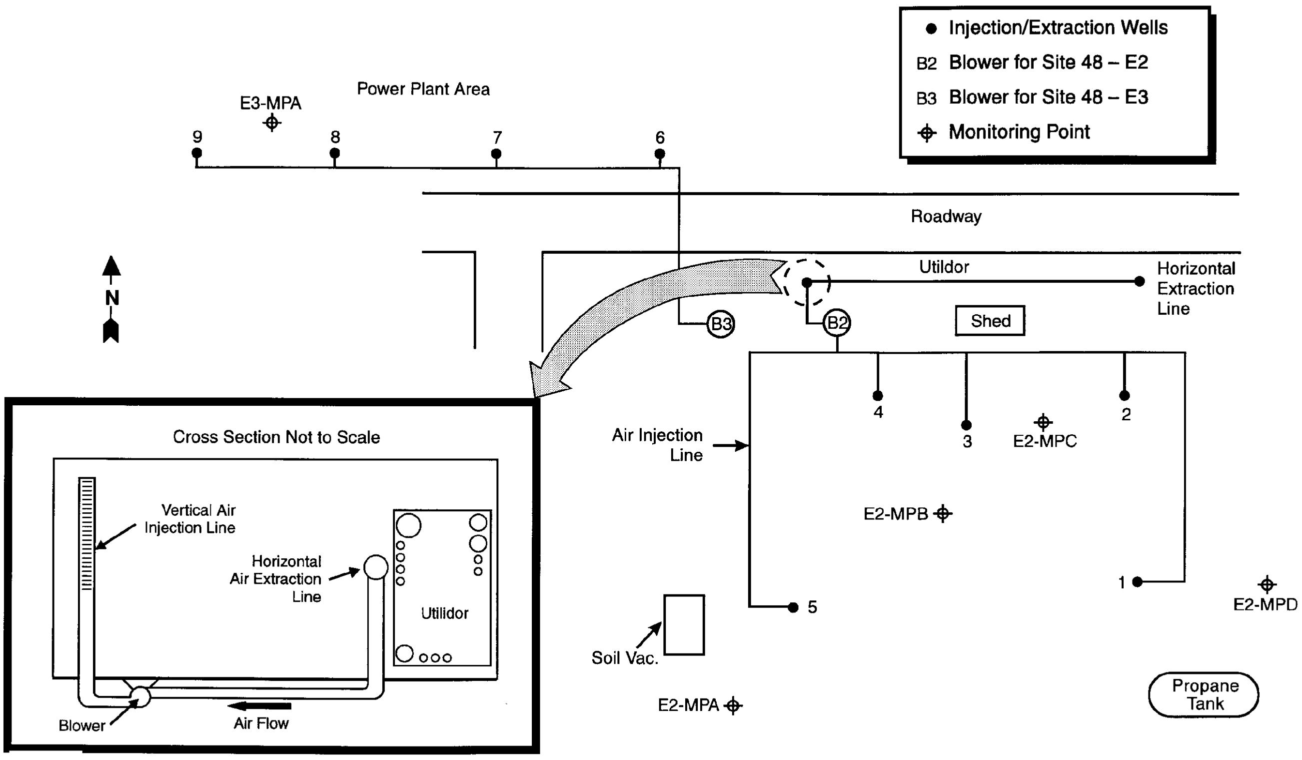
2.3 Well Spacing

To determine the required number of wells and appropriate spacing, an estimate of the radius of influence is necessary. Many approaches to obtaining this estimate are possible, but those normally in use are:

- Based upon measured pressure in monitoring points during a soil gas permeability test.
- Estimated from air flow and oxygen consumption.
- Measured empirically.

Estimating the radius of influence based on pressure measurements during an in situ permeability test is a common approach used in soil venting or soil vapor extraction and is probably the fastest method. This calculation is normally performed by plotting the log of pressure versus distance, as described in Section 1.5.1. The limitation to this approach is that it only incorporates one of the three factors affecting the radius of influence. To determine more exactly the radius of oxygen influence, air flow rate and oxygen utilization need to be considered. In low-permeability soils, a pressure effect may be seen in a monitoring point, but air flow rates to that point may be too low to supply adequate oxygen. Conversely, in a high-permeability soil, air flow rates sufficient to supply oxygen may occur at pressure differentials that cannot be measured. In the authors' experience, if a pressure criterion of 0.1″ H_2O (25 Pa) is used, the estimated radius of influence will be conservative for well spacing and site aeration.

Radius of influence can be estimated for a given air flow rate based on oxygen utilization. Assuming the use of a vertical well so that air flow can be described in cylindrical coordinates and assuming that the radius of influence is much greater than the well radius, the following equation may be used:



Not to Scale

Figure 2-13. Soil gas extraction to isolate a subsurface structure at Site 48, Eielson AFB, Alaska.

$$R_I = \sqrt{\frac{Q(20.9\% - 5\%)}{\pi\, h\, k_o\, \theta_a}} \qquad \text{(Eq. 2-3)}$$

where:

R_I = radius of influence (ft)
Q = air flow rate (ft^3/day)
20.9% - 5% = oxygen %
h = aerated thickness (ft)
k_o = oxygen utilization rate (%/day)
θa = air filled porosity (cm$^3_{air}$/cm$^3_{soil}$)

Example 2-3. Calculation of Radius of Influence: To calculate the radius of influence at Dover AFB, Equation 2-3 is used with the following parameters:

Q = 20 cfm (570 L/min) = 28,800 ft^3/day (820,800 L/day); k_o = 4 %/day; θ_a = 0.25; h = 20 ft (6.1 m)

$$R_I = \sqrt{\frac{\left(28{,}800\ \frac{\text{ft}^3}{\text{day}}\right)(20.9\% - 5\%)}{\pi\ (20\ \text{ft})(4\%/\text{day})(0.25)}}$$

(Eq. 2-4)

Therefore, the radius of influence at this site is equal to approximately 85 ft (26 m).

In practice, the best approach is to estimate the radius of influence from both pressure measurements and oxygen utilization. This incorporates all three of the key factors: pressure connection, air flow, and oxygen utilization. The authors have never found in practice a site where this combined approach has overestimated the radius of influence.

The most conclusive determination of radius of influence is empirical measurement. The blower can be started and oxygen levels measured in monitoring points. The problem with this approach is that a minimum of several days is required to reach steady state. At some sites, more than 30 days are required.

Well spacing typically is 1 to 1.5 times the radius of influence. When multiple wells are installed, some consideration may be given to air flow patterns. In theory, air flow lines may develop that create "dead zones"; however, given vertical and horizontal flow paths and diffusion, these dead zones are unlikely to occur, so compensating for them is not routinely recommended.

2.4 Blowers and Blower Sizing

A blower provides the driving force to move air through the bioventing system. In selecting a blower size, important points to consider are the required air flow rate and the total system pressure drop. System pressure drop includes the back pressure due to the vent wells and formation in an air injection configuration (or the vacuum induced in the wells and formation in an extraction configuration) plus any pressure drop in the system piping and off-gas treatment system. This section describes the procedure for sizing a blower and uses a specific example to illustrate the procedure.

The two basic types of blowers are centrifugal machines and positive displacement machines. Positive displacement blowers are further subdivided into rotating machines and reciprocating machines (Figure 2-14). Selection of the appropriate type and size is based on the air flow requirement and the suction and discharge pressures presented to the blower during operation at the design air flow rate. Centrifugal blowers are generally favored when air flow requirements are high and/or the system pressure drop is low. Rotating positive displacement blowers generally provide lower air flow capacity and higher pressures than centrifugal blowers but can generate moderate to high vacuum at the blower inlet. Because of their vacuum capability, rotating positive displacement blowers may be used for systems operating in an extraction configuration. Reciprocating positive displacement machines are typically used for applications requiring very high pressure. Except for single-action diaphragm pumps used for soil gas sampling, reciprocating positive displacement pumps are rarely used in bioventing applications and are not discussed further. The required pressure or vacuum in the well is a function of the soil gas permeability, which is determined through field tests as described in Section 1.5.

2.4.1 Centrifugal Blowers

Centrifugal blowers impart energy to the air stream by means of a rapidly rotating impeller or propeller. The moving impeller imparts kinetic energy to the fluid. Part of the added kinetic energy is then converted to pressure head in the blower casing as the fluid leaves the impeller. Examples of centrifugal blowers include radial blowers, regenerative radial blowers, multistage radial blowers, and axial blowers.

In a radial blower, air enters at the center of the housing and is picked up by an impeller vane near the axis of rotation (low-velocity area). Air is pushed radially away from the axis of rotation and accelerated by the impeller vane. Air exits the tip of the vane at high speed and

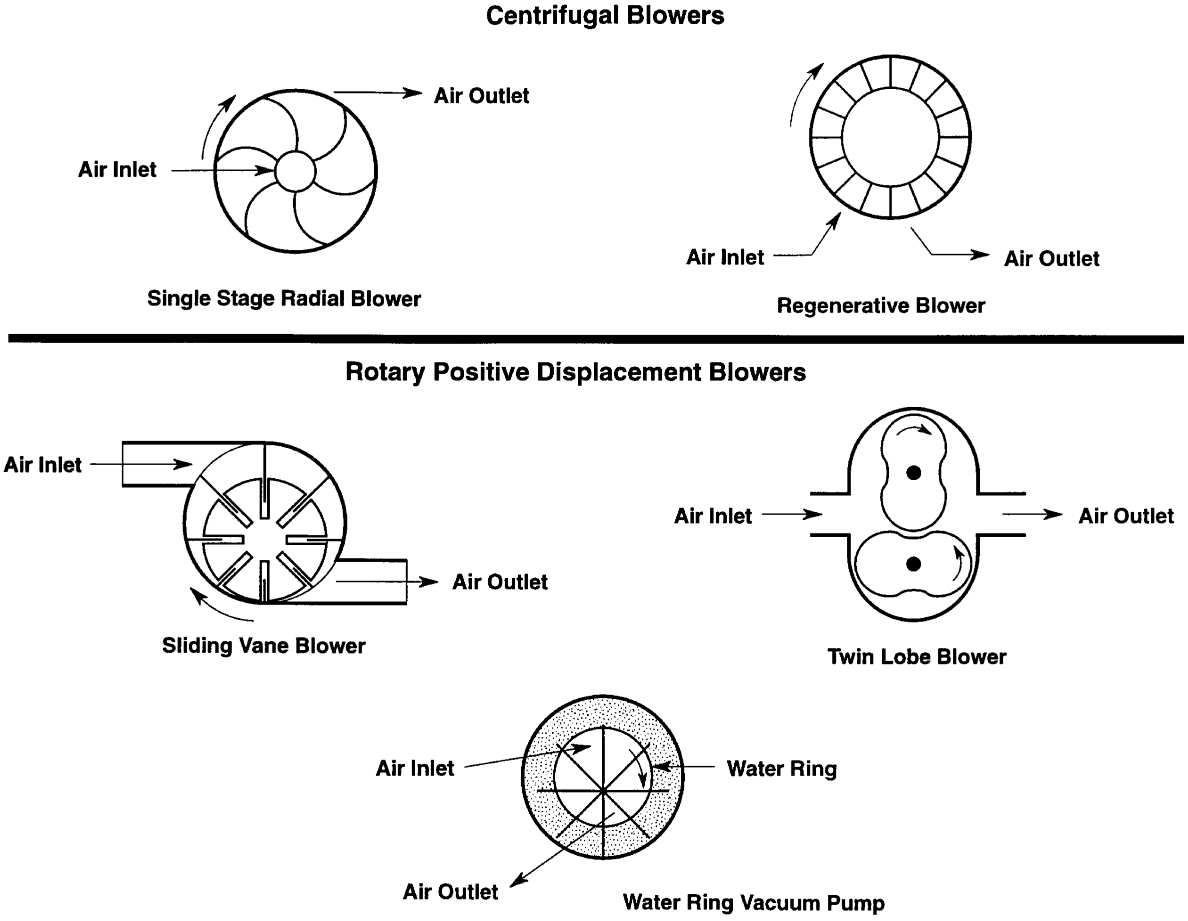


Figure 2-14. Schematic of blower types.

enters the volute casing where the air velocity drops, converting kinetic energy into pressure head.

Regenerative centrifugal blowers provide efficient air movement in the flow rate and pressure drop ranges encountered in soil vapor extraction and bioventing applications and can produce moderate vacuum at the suction port. They are available in nonsparking explosion-proof designs. As a result of these capabilities, the regenerative centrifugal blower is widely used in soil vapor extraction and bioventing systems. Unlike standard single-stage radial centrifugal blowers, the regenerative design uses a short-bladed turbine impeller. As the regenerative blower impeller rotates, centrifugal acceleration moves the air from the base of the blade to the blade tip. The fast-moving air leaving the blade tip flows around the housing contour and back down to the base of the next blade, where the flow pattern repeats. This repeated acceleration allows a regenerative blower to produce higher differential pressure than a conventional single-stage radial flow design. The regenerative blowers can also produce higher vacuum at the suction port compared with a pure radial flow design (but are not able to reach the high vacuum conditions provided by rotary positive displacement blowers).

2.4.2 Rotary Positive Displacement Blowers

Rotary positive displacement blowers impart energy to the air stream by means of a rotating element displacing a fixed volume with each revolution. Examples of rotary positive displacement blowers include twin-lobe blowers, water ring vacuum pumps, sliding vane blowers, and flexible vane blowers. Sliding vane and flexible vane blowers may be used for soil gas sampling or other low-flow applications but have too low an air flow capacity to act as the air handler in a bioventing system. Lobe blowers and water ring vacuum pumps have been used in soil vapor extraction and bioventing systems where moderate to high vacuum is needed.

In a twin-lobe blower, two figure-eight-shaped lobe impellers, mounted on parallel shafts, rotate in opposite directions. As each impeller lobe passes the pump inlet, it traps a volume of gas and carries it around the case to the pump outlet. The rotation speed of the two impellers is controlled so that the volume created at the inlet side of the casing is larger than the volume at the outlet side of the casing, resulting in compression of the air trapped by the impeller lobe.

A water ring vacuum pump uses a rotating vaned impeller in a cylindrical pump casing. The impeller axis of rotation is off center with respect to the pump housing. A uniformly thick layer of water forms on the inside of the pump casing as a result of the rotary action of the impeller. Because the impeller is off center, the cavity formed between two impeller vanes and the water seal changes size as the vanes move around the pump housing. Air enters the pump where the cavity formed by the vanes and the water seal is large and is discharged where the cavity is small, thus increasing the pressure of the pumped gas.

2.4.3 Blower Selection and Sizing

Proper sizing and selection of a blower is essential to ensure that the unit can deliver the required air flow and that the unit operates properly. Choosing the wrong blower can result in an inability to deliver sufficient oxygen or a significantly shortened blower life. Care must be taken to select the type of blower that can deliver the required air flow at the expected pressure. The best approach is to select a blower that allows operation near the middle of its performance range. A blower operating near its maximum pressure/vacuum is running inefficiently and under stressed conditions, thereby increasing operating costs and shortening blower life. Selection of an oversized blower also reduces operating efficiency and unnecessarily increases capital costs. Example 2-4 illustrates a typical decision process for selection and sizing of a blower.

Example 2-4. Selection and Sizing of a Blower: For the site described in Example 2-2, 16 cfm (453 L/min) of air must be delivered to the example treatment cell. Based on the soil gas permeability test conducted at the site, operating pressures of 10″H_2O (2.5×10^3 Pa) were required to deliver 16 cfm (453 L/min). A regenerative air blower is selected because it operates efficiently at the specified flow rate and pressure. Blower performance curves were obtained for three different-sized blowers (1/10, 1/8, and 2½ hp, respectively), all of which might be expected to produce 16 cfm (453 L/min). The curves are shown in Figure 2-15.

The performance curves indicate that Blower #1 is too small and would not be able to provide 16 cfm (453 L/min) at 10″H_2O (2.5×10^3 Pa). Although Blower #3 could provide 16 cfm (453 L/min) at 10″H_2O (2.5×10^3 Pa), it would be operating at the lower end of performance and would be too big. The performance curve for Blower #2 shows that it would be a good choice. Blower #2 is rated to deliver as much as 21 cfm (595 L/min) at 10″H_2O (2.5×10^3 Pa). The excess air flow can be bypassed to the atmosphere, allowing adjustment for the 16 cfm (453 L/min) flow into the vent. If volatilization is not a concern and the additional air flow is not a problem, the entire flow can be injected into the vent well.

The example described above is a simplified case to show how to select and size a blower for use with bioventing. Situations in the field may become more complicated if significant seasonal variations occur in soil gas permeability or if other parameters exist that

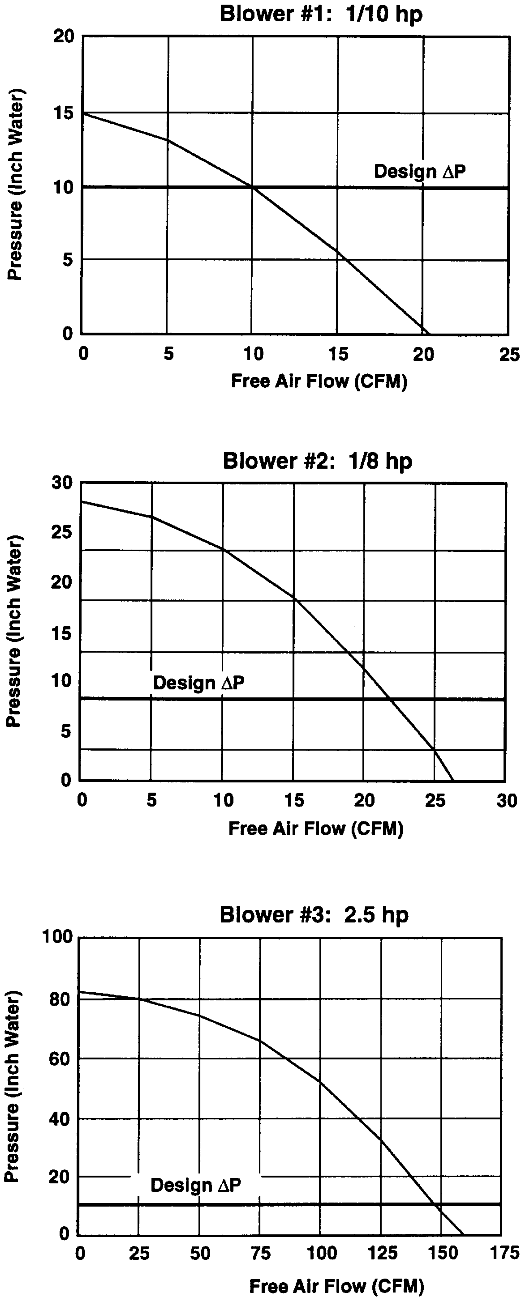


Figure 2-15. Performance curves for three different-sized blowers (1/10, 1/8, and 2.5 hp, respectively).

affect gas flow and oxygen demand. The key design consideration is to select and size a blower based on conditions when oxygen demand is highest and soil gas permeability is lowest. Incorporating a bypass into the system plumbing reduces the air flow delivered to the soil. Air flow cannot be increased above the performance of the blower, so the blower should be selected for the most demanding conditions. The operating principles of several blower types are outlined in the following sections. Further information on pumps and blowers may be found in Pumping Manual, 1989; Karassik et al., 1991; and Graham, 1949.[4]

2.5 Vent Well Construction

Vent well construction is fairly standard, and general guidelines are provided here. If existing ground-water monitoring wells at the site are screened above the water table, they can be used as vent wells. This option is appropriate for air injection systems but is less successful for air extraction systems because the applied vacuum causes a rise in the water table that could submerge the screened interval.

The diameter of the vent well typically is between 2 in. and 4 in. (5.1 cm and 10 cm), although larger and smaller diameters have been successfully used. Vent well diameter depends on the soil type, ease of drilling, and area and depth of the contaminated volume. In most shallow or sandy soils, a 2-in. diameter (5.1-cm) vent well provides adequate air flow for bioventing. For sites with contamination extending below 30 ft (9.1 m) or in low-permeability soils, a 3-in. or 4-in. (7.6-cm or 10-cm) vent well is recommended because it allows for greater air flow to aerate a greater volume. As the depth of well increases, the fractional cost of well construction materials per ft of well decreases significantly.[5]

The vent well typically is constructed of schedule 40 polyvinyl chloride (PVC) and should be screened with a slot size that maximizes air flow through the soil. The screened interval should extend through as much of the contaminated profile as possible, with the bottom of the screen corresponding to the lowest historical level of the water table. When designing a screen for an extraction well, the potential for water table upconing must be considered. If the bottom of the screened interval is close to the water table, water will be pulled into the vent well, reducing its effectiveness. If screening below the water table is necessary, additional screened length above the water table may be necessary to offset water table upconing.

Hollow-stem augering is the most common drilling method; however, a solid-stem auger is acceptable in more cohesive soils. The AFCEE is also investigating the use of cone penetrometer (CPT) wells for bioventing. Many other drilling techniques are also appropriate. In shallow, softer soils, hand-augering may be feasible. Wherever possible, the diameter of the borehole should be at least two times greater than the vent well outside diameter. The annular space corresponding to the screened interval should be filled with silica sand or an equivalent. The annular space above the screened interval should be sealed with a bentonite and grout slurry to prevent short-circuiting of air to or from the surface. The construction detail of a typical vent well is shown in Figure 2-16.

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[4] See Appendix B for recommended specifications and manufacturers for the blowers.

[5] See Appendix B for recommended specifications and manufacturers for vent well construction materials.

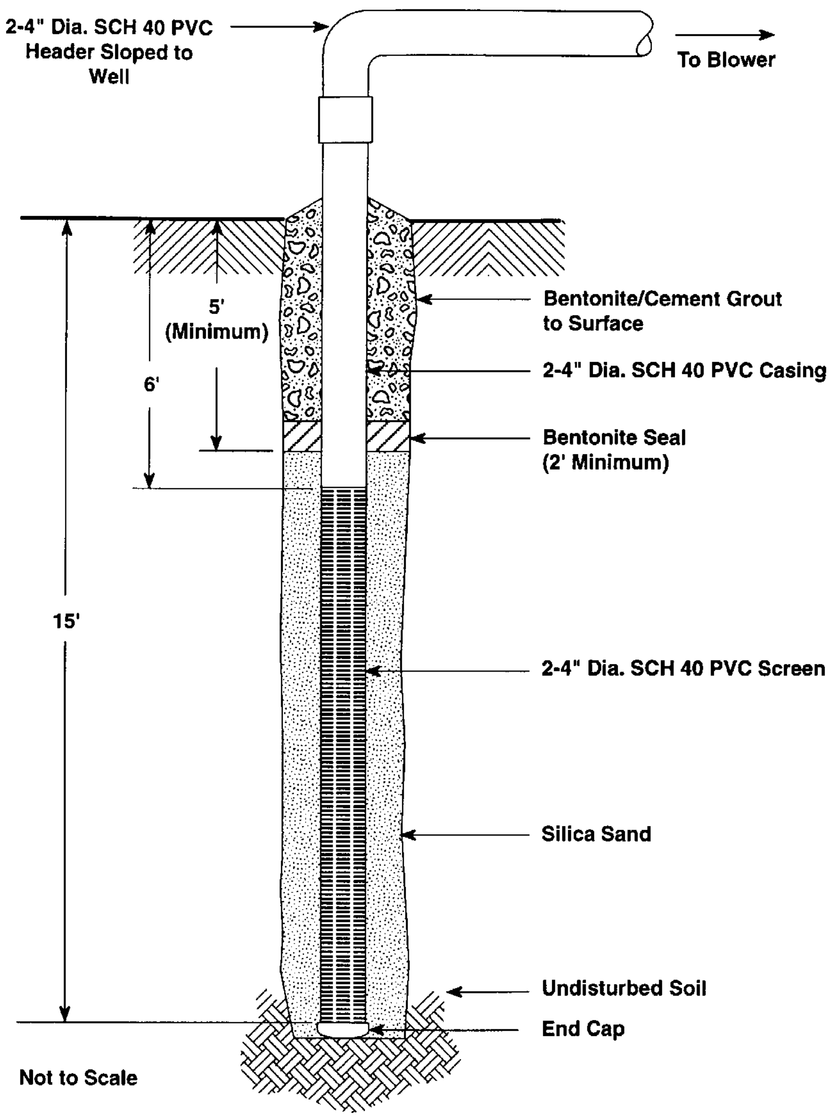

Figure 2-16. Schematic of a typical vent well.

To maintain the integrity of the vent well seal, as a rule of thumb, do not allow injection pressures measured in water depth to exceed the total grouted and sealed length. For example, in a well with 3 ft (0.91 m) of bentonite seal and 3 ft (0.91 m) of grout, do not exceed an injection pressure of 72″H_2O (1.8×10^4 Pa). High pressures also can damage seals. If the injection pressure exceeds the bearing capacity of the soil, fracturing is possible. Care must be taken with injection wells to obtain a good seal. Injection wells should be installed with a bentonite and grout slurry. Dry bentonite chips do not provide an adequate seal unless the chips are continuously hydrated during installation.

2.6 Monitoring Point Construction

Soil gas monitoring points are used for pressure and soil gas measurements and are a very important component of a bioventing system. Proper construction of monitoring points is essential for monitoring localized pressure and soil gas concentrations. To the extent possible, the monitoring points must be located in contaminated soils with greater than 1,000 mg/kg of total petroleum hydrocarbon. If monitoring points are not located in contaminated soil, meaningful in situ respiration data cannot be collected.

In addition, location of monitoring points should consider soil gas permeability testing and radius of influence determination. Monitoring points should be located at varying distances from the vent well. The distances from the vent well vary depending on soil type; suggested monitoring point spacing is shown in Table 2-3.

In practice, each monitoring point cluster usually is screened to at least three depths. The deepest screen should be placed either at or near the bottom of contamination if a water table is not encountered, or a minimum of 2 ft to 3 ft (0.61 m to 0.91 m) above the water table if

Table 2-3. Recommended Spacing for Monitoring Points

Soil Type	Depth to Top of Vent Well Screen (ft)[a]	Spacing Interval (ft)[b]
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
Clay	5	10-20-30
	10	10-20-40
	>15	10-25-50

it is encountered. Consideration should be given to potential seasonal water table fluctuations and soil type in finalizing the depth. In more permeable soil, the monitoring point can be screened closer to the water table. In less permeable soil, it must be screened further above the water table. The shallowest screen normally is 3 ft to 5 ft (0.91 m to 1.5 m) below land surface. The intermediate screen should be placed at a reasonable interval at a depth corresponding to the center to upper quarter of the depth of the vent well screen. In some cases, additional screened depths may be desirable to more fully monitor the contaminated interval, to monitor differing stratigraphic intervals, or to adequately monitor deeper sites with broadly screened vent wells.

Example 2-5. Selection of Depth Intervals for Monitoring Points: Site soils are sandy, with ground water at 30 ft (9.1 m). The vent well was screened from 17.5 ft to 27.5 ft (5.3 m to 8.4 m) below land surface. Therefore, monitoring point depth intervals chosen were 28 ft (8.5 m), 22.5 ft (6.9 m), and 3 ft (0.91 m). For sites with vent wells deeper than 30 ft (9.1 m), more depths may be screened, depending on stratigraphy.

Monitoring point construction varies depending on the depth of drilling and the drilling technique. Monitoring points consist of a small-diameter ¼-in. (0.64-cm) tube to the specified depth with a screen approximately 6 in. (15 cm) long and 1 in. (2.5 cm) in diameter. In shallow, open-hole installations, rigid tubing (i.e., schedule 80 ¼-inch [0.64 cm] PVC) terminating in the center of a gravel or sand pack may be adequate. The gravel or sand pack normally should extend for an interval of 1 ft to 2 ft (0.30 m to 0.61 m), with the screen centered. In low-permeability soils, a larger gravel pack may be desirable. In wet soils, a longer gravel pack with the screen near the top may be desirable. A bentonite seal at least 2 ft (0.31 m) thick normally is required above and below the gravel pack. Figure 2-17 shows the construction detail of a typical monitoring point installation.[6] For relatively shallow installations in more permeable soils, a hand-driven system may be used. In such a system, a sacrificial drive point with Tygon, Teflon, or other appropriate tubing is driven to the desired depth. Then the steel outer tubing is retrieved, leaving the drive point and the inner flexible tubing in place. Because this type of installation allows little or no sand pack or seal placement, it should be used only in relatively permeable soils where sample collection will not be a problem or in soils that will "self-heal" to prevent short-circuiting. Surface completion of the hand-driven points should be the same as for those installed in borings.

Monitoring points typically are used to collect soil gas for carbon dioxide and oxygen analysis in the 0 percent to 25 percent range, and for hydrocarbons greater than 100 ppmv. The tubing material must have sufficient strength and be nonreactive. Materials used include nylon and Tygon. Sorption and gas interaction with the tubing materials have not been significant problems for this application. If a monitoring point will be used to monitor specific organics in the low-ppm or ppb range, Teflon or stainless steel may be necessary. This is uncommon, however.

A sufficient number of monitoring points should be installed to ensure representative sampling. The actual number installed is site-specific and is driven primarily by plume size and cost of installing and monitoring additional monitoring points. If air injection is being considered in the bioventing test, a nest of monitoring points must be located between the vent well and any buildings that may be at risk to ensure that they are well beyond the radius of influence or that vapor-phase hydrocarbons biodegrade before air reaches the structure.

Temperature monitoring typically is conducted by attaching thermocouples to monitoring points. Type J or K thermocouples can be used and should be attached to the monitoring point depth of interest. In general, soil temperatures vary little across a site but do vary with depth to the ground surface; therefore, few thermocouples are required for adequate soil temperature monitoring at a given site.

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[6] See Appendix B for recommended specifications and manufacturers for monitoring point construction materials.

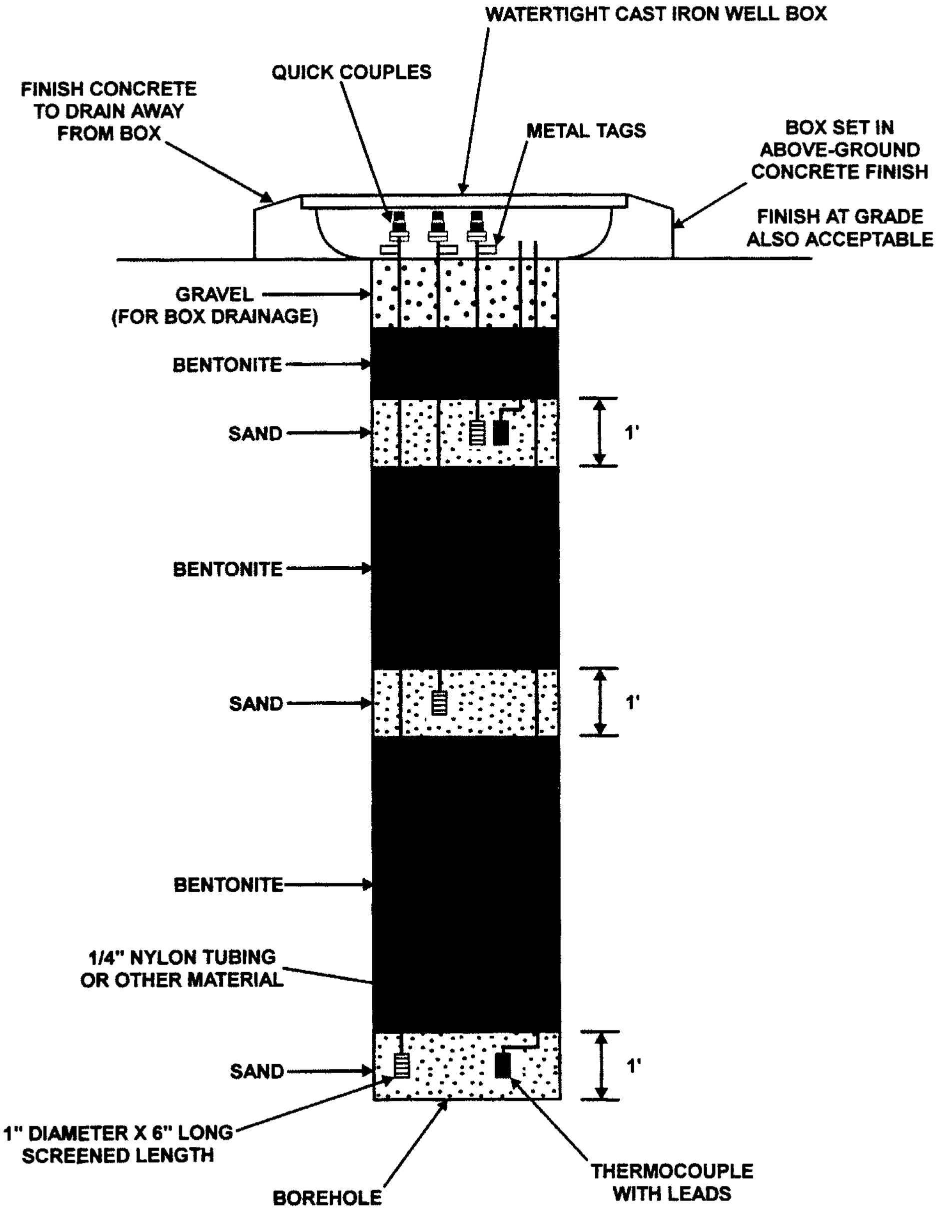

Figure 2-17. Schematic of a typical monitoring point construction.

Chapter 3
Performance Monitoring

The following sections provide suggestions for monitoring bioventing systems. These methods provide a means of tracking the performance of a bioventing system over time. Methods discussed include:

- Soil gas monitoring
- In situ respiration testing
- Surface emissions sampling
- Operation and maintenance of the bioventing system

In addition, the following nonroutine or optional methods are discussed:

- Quantification of biodegradation and volatilization of hydrocarbons during extractive bioventings.
- Qualitative validation of biodegradation through stable carbon isotope monitoring.

3.1 Soil Gas Monitoring

Periodic soil gas monitoring should be conducted to ensure that the bioventing site is well oxygenated.[1] Initially, soil gas should be monitored weekly until the site becomes fully aerated. Once full aeration is achieved, bioventing system operation can be optimized. After this initial period, soil gas monitoring normally is conducted semiannually for the first year, during the warmest and coldest months, and annually thereafter. If conducting an in situ respiration test during different seasons is not possible, then it should be conducted during the same seasons as the initial test. Because of the relative simplicity of most bioventing systems, frequent soil gas monitoring rarely is necessary to ensure proper operation.

3.2 In Situ Respiration Testing

In situ respiration testing should be conducted periodically as a means of monitoring the progress of site remediation.[2] As the site remediation progresses and contaminant concentrations decrease, in situ respiration rates should approach those measured in the uncontaminated area. Frequent in situ respiration tests are not necessary. In situ respiration tests normally are conducted quarterly for the first year and annually thereafter.

In situ respiration tests for performance are conducted somewhat differently than the test for site characterization described in Section 1.3. During system operation, an in situ respiration test is conducted by first measuring soil gas concentrations of oxygen, carbon dioxide, and total hydrocarbons during system operation. After these measurements are collected, the bioventing system is turned off, and soil gas monitoring is conducted periodically to measure oxygen disappearance and carbon dioxide production. No inert tracer gas is added at this time because the initial testing should have determined whether diffusion or monitoring point leakage was occurring. Calculation of biodegradation rates is accomplished in the same manner as described in Section 1.3.

In situ respiration testing should be used as the primary indicator for site closure. A good indication that the site is remediated and that final soil sampling can be conducted is an in situ respiration rate in the contaminated area similar to that in the uncontaminated area. In situ respiration testing to determine remediation success is economically significant because soil sampling is not relied upon as the sole indicator of site remediation, thus eliminating the high cost of intermediate soil sampling.

In situ respiration rates can be expected to vary with time. Generally, temperature is the most significant driver of short-term (within 1 year) changes. Over longer periods, contaminant reduction decreases rates. One frequently observed phenomenon is a substantial decline in rates from the initial in situ respiration rates to subsequent measurements. This phenomenon seems to result from placement of monitoring points in less contaminated soils. NAPL contamination usually is distributed in a very heterogeneous manner. Under nonventing conditions, volatilization spreads hydrocarbons in soil gas, resulting in more heterogeneous contamination. Soil contaminated in this fashion, however, has a much lower total concentration because sorbed hydrocarbons are present at much lower levels than in soils actually containing NAPLs. If a monitoring point is

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[1] See Sections 1.2, "Soil Gas Survey," and 1.4, "In Situ Respiration Testing," for more detail on sampling and analyzing soil gases.

[2] See Section 1.4, "In Situ Respiration Testing," for additional detail.

placed in this soil with only sorbed and vapor-phase contamination, the initial rates will be high; however, remediation will rapidly reduce the sorbed concentrations and the in situ respiration rates will fall quickly, often by a factor of 5 to 10 in a few months. One indication of this is a low-rate apparent first-order oxygen decay curve, resulting in misleading rate data. Eliminating this problem is difficult; however, placement of monitoring points in the most highly contaminated soil can limit the problem.

3.3 Quantification of Biodegradation and Volatilization of Hydrocarbons During Extractive Bioventing

Biodegradation and volatilization of hydrocarbons can be quantified during extractive bioventing through direct measurement of off-gas concentrations of oxygen and carbon dioxide. Bioventing systems that are operating in injection mode have been reconfigured briefly to provide these data. Note, however, that in the case of injection mode systems, reconfiguration to extraction mode provides an overestimate of the mass of hydrocarbons volatilized because the size of the in situ bioreactor is reduced.[3]

The mass of hydrocarbons volatilized can be calculated as follows:

$$HC_{vol} = \frac{C_{V,HC}}{10^6} \times Q \times \rho_{hexane} \times MW_{hexane} \times \frac{kg}{1{,}000\ g} \times \frac{1{,}440\ min}{day} \qquad \text{(Eq. 3-1)}$$

where:

HC_{vol} = mass of hydrocarbons volatilized (kg/day)
$C_{V,HC}$ = concentration of hydrocarbons in extracted off-gas (ppmv)
Q = flow rate (L/min or cfm)
ρ_{hexane} = density of hexane (moles/L)
MW_{hexane} = molecular weight of hexane (g/mole)

The mass of hydrocarbons biodegraded can be calculated as follows:

$$HC_{bio} = \left(\frac{C_{V,bkgd} - C_{V,O_2}}{100}\right) \times Q \times C \times \rho_{O_2} \times MW_{O_2} \times \frac{kg}{1{,}000\ g} \times \frac{1{,}440\ min}{day} \qquad \text{(Eq. 3-2)}$$

where:

HC_{bio} = mass of hydrocarbons biodegraded (kg/day)
$C_{V,bkgd}$ = concentration of oxygen in background, uncontaminated area (%)
C_{V,O_2} = concentration of oxygen in extracted off-gas (%)
C = mass ratio of hydrocarbon to oxygen degraded based on stoichiometry[4] (1/3.5)

Example 3-1 illustrates these calculations.

Example 3-1. Calculation of Volatilization and Biodegradation of Contaminants During Extraction: At a site undergoing extraction, concentrations of oxygen and TPH in the extracted soil gas at steady state are 19 percent and 140 ppmv, respectively. The system is operating at a flow rate of 4 cfm (113 L/min). Background oxygen concentrations are consistently at 20.9 percent. First, the mass of hydrocarbons volatilized must be calculated.

Given the following parameters:

$C_{V,HC}$ = 140 ppmv; Q = 4 cfm (113 L/min); ρ_{hexane} = 0.042 moles/L; and MW_{hexane} = 84 g/mole.

Using Equation 3-1:

Solving, the mass of hydrocarbons volatilized is 0.081 kg/day (0.18 lb/day).

$$HC_{vol} = \left(\frac{140\ ft^3\ hexane}{10^6\ ft^3\ air}\right)\left(4\ \frac{ft^3}{min} \times \frac{28.3\ L}{ft^3}\right)\left(0.042\ \frac{mole}{L}\right)\left(84\ \frac{g}{mole}\right)\left(\frac{kg}{1{,}000\ g}\right)\left(\frac{1{,}440\ min}{day}\right)$$

To calculate the mass of hydrocarbons biodegraded, use Equation 3-2:

$$HC_{bio} = \left(\frac{20.9 - 19.0}{100}\right)\left(4\ \frac{ft^3}{min} \times \frac{28.3\ L}{ft^3}\right)\left(\frac{1\ g\ HC}{3.5\ g\ O_2}\right)\left(0.042\ \frac{mole}{L}\right)\left(32\ \frac{g}{mole}\right)\left(\frac{kg}{1{,}000\ g}\right)\left(\frac{1{,}440\ min}{day}\right)$$

Solving, the mass of hydrocarbons biodegraded is approximately 1.2 kg/day (2.6 lb/day), or nearly an order of magnitude greater than the amount volatilized.

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[3] See Section 2.1 for a discussion of these issues.

[4] See Section 1.4.2 for a discussion of stoichiometry.

The fraction of total removal by biodegradation is larger for injection systems because the opportunity for biodegradation is greater. In an injection mode, vapors are pushed through the contaminated zone into the uncontaminated zone, allowing for additional biodegradation. When the system is operated in an extraction mode, however, much of the vapor is removed from the soil before biodegradation can occur.

3.4 Surface Emissions Sampling

Surface emissions sampling is not necessary at most bioventing sites. Under the Bioventing Initiative, it was conducted at only five of 125 sites to quantify volatilization of contaminants attributed to air injection. Although surface emissions typically do not occur or are very low at bioventing sites because of low air flow rates, possible surface emissions often are a regulatory concern and surface emission rates may need to be quantified to obtain regulatory approval for bioventing. Note, however, that according to the EPA document *Estimation of Air Impacts for Bioventing Systems Used at Superfund Sites* (U.S. EPA, 1993), emissions from bioventing sites operating in an injection mode are thought to be minimal. Thus, they are not discussed in this document.

One standard surface emission sampling protocol using isolation flux chamber procedures is described by Dupont (1988) and EPA (1986) and is illustrated in Figure 3-1.

The system consists of a square Teflon box that covers a surface area of approximately 0.45 m^2. The box is fitted with inlet and outlet ports for the entry and exit of high-purity air. Inside the box is a manifold that delivers the air uniformly across the soil surface. The same type of manifold is fitted to the exit port of the box. This configuration delivers an even flow of air across the entire soil surface under the box to generate a representative sample.

The air exiting the Teflon box is directed to a sampling box that contains a sorbent tube and a pump. Also attached to the box is a purge line that accommodates the excess flow from the Teflon box that is not drawn into the sorbent tube. A Magnehelic gauge is used to indicate if zero pressure is being maintained on the entire system.

In all cases, a totally inert system is employed. Teflon tubing and stainless steel fittings prevent any contribution to or removal of organics from the air stream. The pump is located on the back side of the sorbent trap so that it is not in a position to contaminate the sample flow.

To calculate the actual emission rates of organic compounds from the soil surface into the atmosphere, the following formula for dynamic enclosure techniques is employed (EPA, 1991a):

$$F = \frac{C_V V_r}{A} \qquad \text{(Eq. 3-3)}$$

where:

F = flux in mass/area-time (g/m^2-min)

C_V = concentration of the gas in units of mass/volume (g/m^3)

V_r = volumetric flow rate of sweep gas (m^3/min)

A = soil surface area covered by enclosure (m^2)

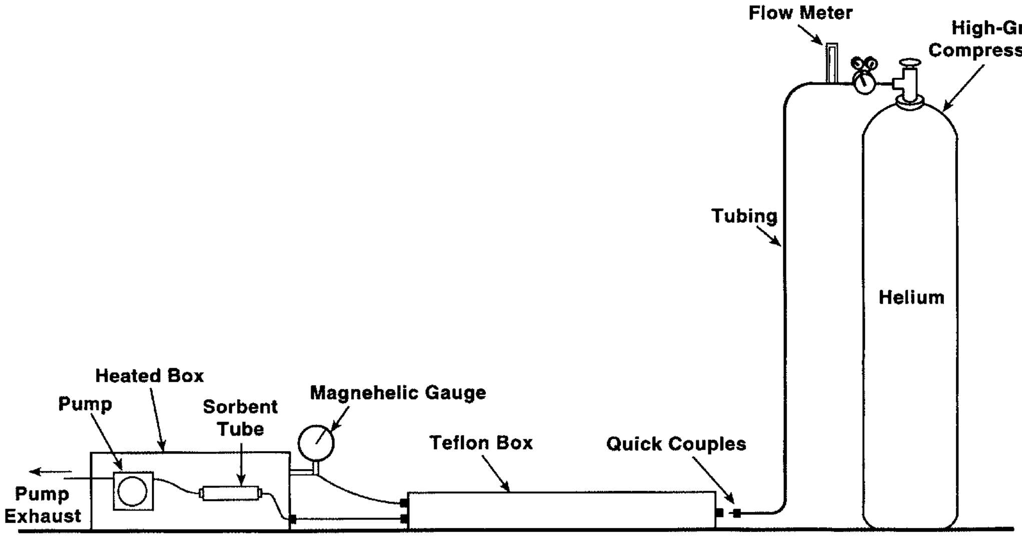


Figure 3-1. Schematic of a surface emissions monitoring device.

At bioventing sites where surface emissions have been measured, surface emissions rates of BTEX and TPH have been several orders of magnitude below regulatory levels. These results have provided strong support for continued operation of bioventing systems in injection mode. As an example, Table 3-1 illustrates surface emissions results from six bioventing sites. In general, surface emissions are very low, with TPH emission rates less than 1 lb/day. These emission rates are well below most regulatory limits and illustrate that properly designed bioventing systems create no significant air emissions.

3.5 Optional Monitoring: Qualitative Validation of Biodegradation Through Stable Carbon Isotope Monitoring

Measurement of stable carbon isotope ratios may help substantiate biodegradation (Aggarwal and Hinchee, 1991). 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 (Suchomel et al., 1990; Stahl, 1980; McMahon et al., 1990). As shown in Figure 3-2, 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. This measurement is not required to validate biodegradation since the in situ respiration test is used for this purpose; therefore, it should only be conducted if dictated by regulatory concerns.

3.6 Operation and Maintenance

Bioventing systems are very simple, with minimal mechanical and electrical parts. If the system is operated

Table 3-1. Surface Emissions Sampling at Bioventing Sites

Base	Site Type	Air Injection Depth (ft)	Air Injection Rate (cfm)	Area of Influence (ft^2)	Total Flux Estimate (lb/day)
Beale AFB, CA	Fire Training Pit	10 - 25	30	6,500	0.15
Bolling AFB, DC	Diesel Spill	10 - 15	20	5,100	0.44
Eielson AFB, AK	JP-4 Spill	6.5 - 13	30	43,600	0.011
Fairchild AFB, WA	JP-4 Spill	5 - 10	15	5,100	0.33
McClellan AFB, CA	JP-4 Spill	10 - 55	50	9,700	0.066
Plattsburgh AFB, NY	Fire Training Pit	10 - 35	13	11,500	0.44

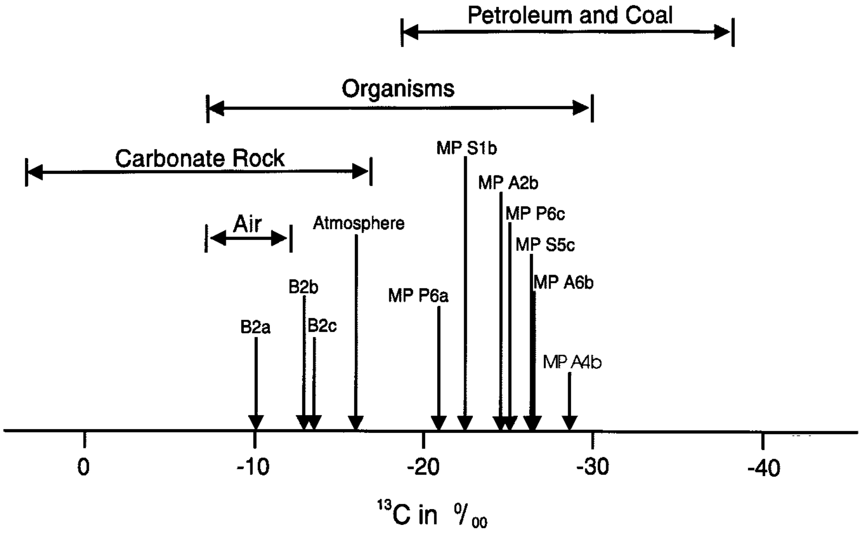


Figure 3-2. Carbon isotopic compositions of soil gas carbon dioxide at Site 20, Eielson AFB, Alaska, August 1993.

in an injection mode, a simple visual system check would be required to ensure that the blower is operating within its intended flow rate and pressure range. Weekly system checks are desirable. Often, someone on site can conduct these system checks because little technical knowledge of the process is required. Minor maintenance such as replacing filters, flow meters, or gauges may be necessary.

If an extraction system or an extraction/reinjection bioventing system is installed, more intensive maintenance is likely to be required. Extraction systems have knockout drums that require draining and treatment of condensate. In addition, in the case of extraction-only systems, off-gas may need to be monitored regularly to ensure that emissions are within regulatory guidelines. Off-gas treatment systems also require periodic checks to ensure proper operation.

Blowers used for bioventing systems typically last for several years and should not need replacement. To date, two bioventing systems have been operating for 3 years with the original blower in place (Battelle, 1994; Leeson et al., 1995), and of the 125 blowers installed to date under the Bioventing Initiative, only three have required repair or replacement.

Chapter 4
Process Evaluation/Site Closure

4.1 In Situ Respiration Testing

In situ respiration testing should be used as the primary indicator for site closure. As discussed in Section 3.2, as site remediation progresses and contaminants are degraded, the measured in situ respiration rates approach background respiration rates. When the in situ respiration rate in the contaminated area is similar to that in the uncontaminated area, this is a good indication that the site is remediated and final soil sampling can be conducted. Initially, the amount of time necessary for cleanup of the site can be estimated on in situ respiration rates, as shown in Example 4-1.

Example 4-1. Calculation of Remediation Time Based on in Situ Respiration Rates: This example assumes an average oxygen utilization rate of 6 percent oxygen per day and an initial average soil concentration of 6,000 mg TPH/kg soil. The oxygen utilization is related to hydrocarbon degraded by the following equations:

$$C_6H_{14} + 9.5O_2 \rightarrow 6CO_2 + 7H_2O$$

$$k_B = -0.68\ k_o$$

Using the above assumptions, an oxygen utilization rate of 6 percent oxygen per day would correspond to a biodegradation rate of approximately 4.1 mg/kg-day. Given that the initial soil concentration is 6,000 mg/kg, an estimate of cleanup time is calculated as follows:

$$\frac{C_o}{k_B} = \text{cleanup time}$$

$$\frac{6{,}000 \text{ mg/kg}}{4.1 \text{ mg/kg-day}} = 1{,}500 \text{ days} \approx 4 \text{ years}$$

This calculation provides a reasonable “ballpark” estimate of the amount of time necessary to remediate the site. This method tends to underestimate treatment time because k_B decreases over time. At the same time, this calculation overestimates treatment time because it does not consider treatment in the expanded bioreactor. Therefore, the calculation must be coupled with process monitoring to provide field-based evidence that the site actually is remediated within this time. Because of widely variable contaminant concentrations, the average biodegradation rate does not reflect actual biodegradation rates throughout the site; biodegradation rates also may fluctuate with season and as contaminant concentrations decrease. Therefore, process monitoring is an important parameter in determining treatment time.

4.2 Soil Sampling

Soil sampling should not be used as a process monitoring technique. Because of the inherently high variability of hydrocarbons in soils, the number of samples required to produce a meaningful result is prohibitive until contamination levels approach 90 percent to 99 percent cleanup. The amount of soil sampling conducted at a site has a tremendous impact on the cost of the project. Minimizing soil sampling makes a remediation effort much more cost-effective. With bioventing systems, in situ respiration testing can indicate when the site is clean and, therefore, when to collect final soil samples. Regulatory issues usually drive the number of final soil samples collected.

The Department of Natural Resources of the State of Michigan published a guidance document for verification of soil remediation. It also provides several methods for statistical sampling strategies (Michigan Department of Natural Resources, 1994). In addition, it provides information on design of the sampling grid and determination of the upper confidence limit (UCL) of the final mean. The UCL is calculated from the following equation:

$$\text{UCL} = \overline{X} + [t = 0.95(n - 1)]\ S_X \qquad \text{(Eq. 4-1)}$$

where:

UCL = upper confidence limit

X = average contaminant concentration

bracketed term = one-tailed t-test at n-1 degrees of freedom (see Table 4-1 for values)

S_X = standard error of the mean, which is calculated as follows:

Table 4-1. Cumulative t Distribution

	p							
One-Tailed	0.550	0.750	0.080	***0.900***	0.950	0.975	0.990	0.995
Two-Tailed	0.100	0.500	0.600	0.800	0.900	0.950	0.980	0.990
1	0.158	1.000	1.376	***3.078***	6.314	12.706	31.821	63.657
2	0.142	0.816	1.061	1.886	2.920	4.303	6.925	9.925
3	0.137	0.765	0.978	1.638	2.353	3.182	4.541	5.841
4	0.134	0.741	0.941	1.533	2.132	2.776	3.747	4.604
5	0.132	0.727	0.920	1.476	2.015	2.571	3.365	4.032
6	0.131	0.718	0.906	1.440	1.943	2.447	3.143	3.707
7	0.130	0.711	0.896	1.415	1.895	2.365	2.998	3.499
8	0.130	0.706	0.889	1.397	1.860	2.306	2.896	3.355
9	0.129	0.703	0.883	1.383	1.833	2.262	2.821	3.250
10	0.129	0.700	0.879	1.372	1.812	2.228	2.764	3.169
11	0.129	0.697	0.876	1.363	1.796	2.201	2.718	3.106
12	0.128	0.695	0.873	1.356	1.782	2.179	2.681	3.055
13	0.128	0.694	0.870	1.350	1.771	2.160	2.650	3.012
14	0.128	0.692	0.868	1.345	1.761	2.145	2.624	2.977
15	0.128	0.691	0.866	1.341	1.753	2.131	2.602	2.947

$$S_X = \frac{S}{\sqrt{n}} \qquad \text{(Eq. 4-2)}$$

where:

S = standard deviation
n = sample size

If the UCL is higher than the regulatory threshold, then the lambda relationship is used to calculate the appropriate sample size:

$$\lambda = \frac{RT - \overline{X}}{S} \qquad \text{(Eq. 4-3)}$$

where:

λ = statistical parameter (see Table 4-2 for values)
RT = regulatory threshold
X = average contaminant concentration
S = standard deviation

Once λ is calculated, by referring to Table 4-2, the number of additional samples required to verify cleanup can be determined. This calculation is shown in Example 4-2.

Example 4-2. Statistical Evaluation of Contaminant Data: At this site, three preliminary soil samples were collected to estimate a sample mean and standard deviation. The initial sample mean was 90 mg/kg TPH with a standard deviation of 30 mg/kg. The regulatory threshold is 100 mg/kg TPH. Calculating the UCL:

$$UCL = 90 + (2.920) \times \left(\frac{30}{\sqrt{3}}\right) = 141 \text{ mg/kg} \qquad \text{(Eq. 4-4)}$$

Given that this value is above the regulatory threshold, the lambda calculation is performed to determine how many additional samples are required to verify cleanup:

$$\lambda = \frac{100 - 90}{30} = 0.33 \qquad \text{(Eq. 4-5)}$$

From Table 4-2, for $\alpha = 0.05$ and $\beta = 0.05$, a sample size of between 90 and 122 additional samples is required.

Ott (1984) provides an alternative method for estimating final sample size. This method determines the required

Table 4-2. Number of Observations for t Test of Mean

		Level for t test									
Single-Sided **Double-Sided**		**α = 0.01** **α = 0.02**					**α = 0.05** **α = 0.10**				
λ	β	0.011	0.05	0.1	0.2	0.5	0.01	***0.05***	0.1	0.2	0.5
0.05											
0.10											
0.15											122
0.20						139					70
0.25						90			139	101	45
0.30					115	63		***122***	97	71	32
0.35				109	85	47		***90***	72	52	24
0.40			101	85	66	37	101	70	55	40	19
0.45		110	81	68	53	30	80	55	44	33	15
0.50		90	66	55	43	25	65	45	36	27	13
0.55		75	55	46	36	21	54	38	30	22	11
0.60		63	47	39	31	18	46	32	26	19	9
0.65		55	41	34	27	16	39	28	22	17	8
0.70		47	35	30	24	14	34	24	19	15	8
0.75		42	31	27	21	13	30	21	17	13	7
0.80		37	28	24	19	12	27	19	15	12	6
0.85		33	25	21	17	11	24	17	14	11	6
0.90		29	23	19	16	10	21	15	13	10	5
0.95		27	21	18	14	9	19	14	11	9	5
1.00		25	19	16	13	9	18	13	11	8	5

number of soil samples to show a statistical difference between initial and final contaminant concentrations:

$$n = \frac{\sigma^2 (z_\alpha + z_\beta)^2}{(\mu_o - \mu)^2} \qquad \text{(Eq. 4-10)}$$

where:

n = number of final soil samples to collect

σ^2 = population variance of the initial soil sampling event

z_α = probability of a Type I error

z_β = probability of a Type II error

μ_o = mean of the initial soil sampling event

μ = estimated mean of the final soil sampling event

As the difference between the initial and final means increases, the number of samples required to show a statistical difference between the two sampling events decreases. As shown in Table 4-3, as hydrocarbons are further degraded, fewer soil samples are required to show a statistical difference in the two means. This concept is illustrated in Example 4-3.

Example 4-3. Calculation of Final Number of Soil Samples for Site Closure: At this site, 83 initial soil samples were collected with a mean TPH concentration of 6,000 mg/kg and a standard deviation of 8,000 mg/kg (typical of many bioventing sites). The average biodegradation rate at this site was 4.1 mg/kg-day. Given that the system had been operating for 3.5 years, the final mean TPH concentration can be estimated as follows:

$$\begin{gathered}4.1 \text{ mg/kg-day} \times 1{,}278 \text{ days} = \\ 5{,}240 \text{ mg/kg TPH degraded}\end{gathered} \qquad \text{(Eq. 4-11)}$$

$$\begin{gathered}\text{Estimated final [TPH]} = \\ 6{,}000 \text{ mg/kg} - 5{,}240 \text{ mg/kg} = 760 \text{ mg/kg}\end{gathered} \qquad \text{(Eq. 4-12)}$$

Using this estimate of the final mean TPH concentration, the number of samples to be collected to provide statistically significant data can be calculated using Equation (4-4) and the following parameters:

Table 4-3. Calculation of the Number of Samples Required To Show a Statistical Difference Between Means of Two Sampling Events

Time From Initiation of Bioventing (days)	Estimated Amount of Hydrocarbon Degraded (mg/kg)	Estimated Amount of Hydrocarbon Remaining (mg/kg)	Number of Samples Required
180	1,440	4,560	731
365	2,920	3,080	178
540	4,320	1,680	81
730	5,840	160	44

$\sigma = (8{,}000)^2$; $z_\alpha = 1.645$ (for $\alpha = 0.05$); $z_\beta = 2.33$ (for $\beta = 0.01$); $\mu_o = 6{,}000$ mg/kg; $\mu = 525$ mg/kg

Selected z values are shown in Table 4-4. The z_α and z_β are determined by finding areas corresponding to $(0.5 - \alpha)$ and $(0.5 - \beta)$, respectively:

$$n = \frac{(8{,}000)^2(1.645 + 2.33)^2}{(6{,}000 - 760)^2} \qquad \text{(Eq. 4-13)}$$

Therefore, the number of final soil samples that must be collected is 37.

Table 4-4. Selected z Values for Estimation of Final Soil Sample Number (Ott, 1984)

z	0.00	0.01	0.02	0.03[a]	0.04[b]	0.05[b]
0.0	0.0000	0.0040	0.0080	0.0120	0.0160	0.0199
0.1	0.0398	0.0438	0.0478	0.0517	0.0557	0.0596
0.2	0.0793	0.0832	0.0871	0.0910	0.0948	0.0987
0.3	0.1179	0.1217	0.1255	0.1293	0.1331	0.1368
0.4	0.1554	0.1591	0.1628	0.1664	0.1700	0.1736
0.5	0.1915	0.1950	0.1985	0.2019	0.2054	0.2088
0.6	0.2257	0.2291	0.2324	0.2357	0.2398	0.2422
0.7	0.2580	0.2611	0.2642	0.2673	0.2704	0.2734
0.8	0.2881	0.2910	0.2939	0.2967	0.2995	0.3023
0.9	0.3159	0.3186	0.3212	0.3238	0.3264	0.3289
1.0	0.3413	0.3438	0.3461	0.3485	0.3508	0.3531
1.1	0.3643	0.3665	0.3686	0.3708	0.3729	0.3749
1.2	0.3849	0.3869	0.3888	0.3907	0.3925	0.3944
1.3	0.4032	0.4049	0.4066	0.4082	0.4099	0.4115
1.4	0.4192	0.4207	0.4222	0.4236	0.4251	0.4265
1.5	0.4332	0.4345	0.4357	0.4370	0.4382	0.4394
1.6	0.4452	0.4463	0.4474	0.4484	0.4495[b]	0.4505[b]
1.7	0.4554	0.4564	0.4573	0.4582	0.4591	0.4599
1.8	0.4641	0.4649	0.4656	0.4664	0.4671	0.4678
1.9	0.4731	0.4719	0.4726	0.4732	0.4738	0.4744
2.0	0.4772	0.4778	0.4783	0.4788	0.4793	0.4798
2.1	0.4821	0.4826	0.4830	0.4734	0.4838	0.4842
2.2	0.4861	0.4864	0.4868	0.4871	0.4875	0.4878
2.3[a]	0.4893	0.4896	0.4898	0.4901[a]	0.4904	0.4906
2.4	0.4918	0.4920	0.4922	0.4925	0.4927	0.4829
2.5	0.4938	0.4940	0.4941	0.4943	0.4945	0.4846

[a] Corresponds to determining z_β.
[b] Corresponds to determining z_α.

Chapter 5
Costs

Based on Air Force and recent commercial applications of this technology, the total cost of in situ soil remediation using the bioventing technology is \$10 to \$60 per yd^3 (Downey et al., 1994b). At sites with over 10,000 yd^3 of contaminated soil, costs of less than \$10 per yd^3 can be achieved. Costs greater than \$60 per yd^3 are associated with smaller sites, but bioventing can still offer significant advantages over more disruptive excavation options. Operations and maintenance costs are minimal, particularly when base personnel are willing to perform simple system checks and routine maintenance. Table 5-1 provides a detailed cost breakdown of remediation of 5,000 yd^3 of soil contaminated with an average concentration of 3,000 mg of JP-4 jet fuel per kg of soil.

Ward (1992) compared costs of bioventing with costs of other in situ bioremediation technologies (Table 5-2). Costs shown in Table 5-2 reflect actual costs for these three technologies at fuel spills in Traverse City, Michigan. Even though the area treated through bioventing was larger than that treated with hydrogen peroxide or nitrate, total costs for bioventing were significantly lower than for the other technologies.

Figure 5-1 provides a comparison of estimated unit costs for several technologies commonly used for remediation of fuel-contaminated soils. All costs are based on the treatment of soil contaminated with 3,000 mg of JP-4 jet fuel per kg of soil. Costs are provided for the following remediation scenarios: 2 years of in situ bioventing; 1 year of soil vapor extraction with thermal vapor treatment; excavation and 1 year of on-base landfarming with leachate controls; and excavation followed by low-temperature thermal desorption. The cost of reconstructing excavated areas is not included. At many sites with contamination beneath concrete and buildings, bioventing is the only cost-effective treatment option available.

Table 5-1. Typical Full-Scale Bioventing Costs (Downey et al., 1994b)

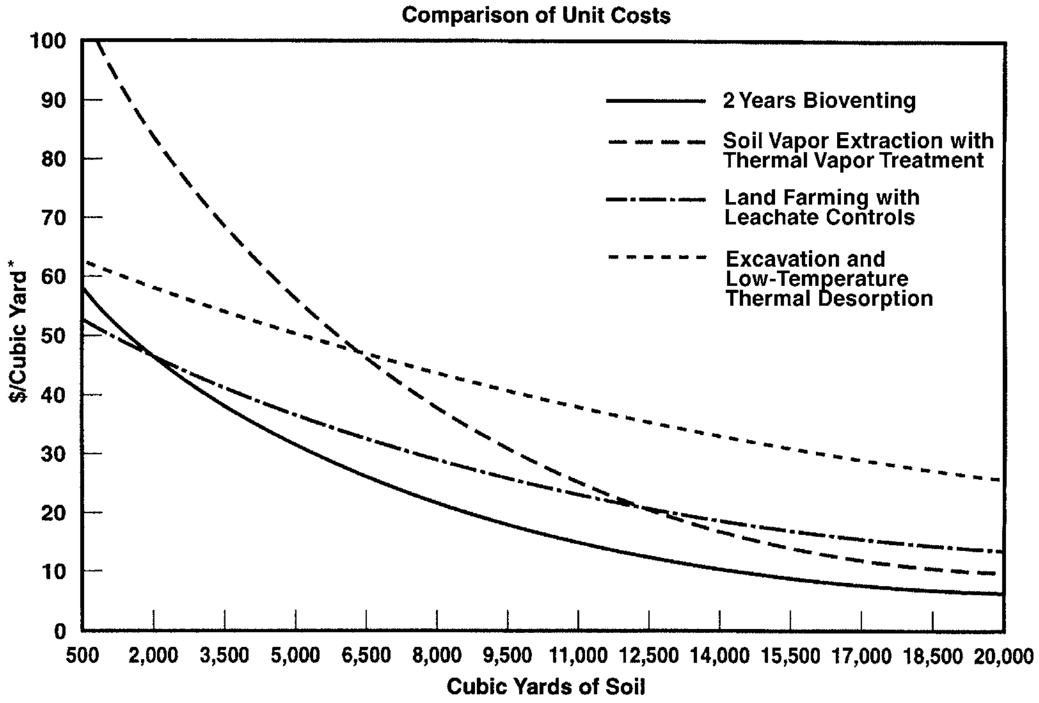
Task	Total Cost (\$)
Site visit/planning	5,000
Work plan preparation	6,000
Pilot testing	27,000
Regulatory approval	3,000
Full-scale construction	
Design	7,500
Drilling/sampling[a]	15,000
Installation/startup	4,000
Two-year monitoring	6,500
Two-year power	2,800
Soil sampling at 2 years	13,500
Total	90,300

[a] Assumes four air injection wells drilled to a depth of 15 ft.

Table 5-2. Cost Comparison of in Situ Bioremediation Technologies Used at Fuel Spill Sites (Ward, 1992)

	Total Costs (\$/m^3 of Contaminated Earth)		
Task	Hydrogen Peroxide	Nitrate	Bioventing[a]
Construction[b]	45	118	26
Labor/monitoring	72	96	40
Chemicals	500	30	0.44
Electricity	24	12	6.8
Total	641	256	73

[a] Values reflect only first 4 months of demonstration.
[b] Prorated to a 5-year service life on buildings, pumps, and blowers.



* Based on treatment of soil contaminated with 3,000 mg of JP-4 jet fuel per kg of soil.
Costs do not include the cost of reconstructing excavated sites.

Figure 5-1. Comparison of costs for various remedial technologies for fuel-contaminated soils (Downey et al., 1994b).

Chapter 6
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Appendix A
Glossary

abiotic not relating to living things, not alive

acidity measure of the hydrogen ion concentration of a solution

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

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

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

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

alkalinity measure of the hydroxide ion concentration of a solution

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

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

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

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

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

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

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

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

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

biomass amount of living matter (in a specified area)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

enzyme biologically produced, protein-based catalyst

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

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

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

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

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

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

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

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

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

nutrients constituents required to support life and growth

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

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

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

ozonation injection of ozone into a contaminated site

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

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

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

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

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

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

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

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

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

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

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

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

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

remediation activity involved with reducing the hazard from a contaminated site

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

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

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

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

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

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

surfactant substance that lowers the surface tension of a liquid

treatability ability of a site to be remediated

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

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

volatile easily vaporized at relatively low temperatures

volatilization process of vaporizing a liquid into a gas

Appendix B
Equipment Specifications and Manufacturers

The products and manufacturers listed in this document are meant as a guidance for environmental managers and consulting engineers. Products or manufacturers are not endorsed by the U.S. Air Force or EPA.

B.1 Soil Gas Survey Equipment

Calibration Gases

Calibration gases include helium, carbon dioxide, oxygen, and hexane. They are available in the appropriate concentrations for each instrument and may require a special regulator depending on the cylinder type.

The calibration gases are used to standardize the gas analyzing instruments.

The gases are sold through Scott Specialty Gases in Troy, Michigan, 313 589-2950. The gases cost approximately $124 depending on the cylinder size and gas desired.

Tedlar Sampling Bag

The 1-L bag is made from transparent Tedlar and has a polypropylene fitting. The bag is approximately 7x7 in. and is sold in packages of 10. The fitting is opened and closed by twisting the cap, which can also be locked into place.

The Tedlar bag is used to store soil gas samples and calibration gases until they can be analyzed by an appropriate gas meter.

The Tedlar bags are supplied by SKC, Eighty Four, Pennsylvania, 800 752-8472. The cost is approximately $82 for 10 bags.

Latex Rubber Tubing

Latex or amber tubing is connected to the Tedlar bag tubing fitting for filling the bag. Tubing is normally cut approximately 4 in. in length. Size of tubing is 1/4-in. outside diameter x 3/16-in. inside diameter and can be purchased from any VWR Scientific location.

Wire/Cable Ties

Nylon cable ties are used like a hose clamp for securing the latex tubing to the Tedlar bag fitting. Cable ties can be purchased from Grainger or any hardware store. The catalog number is 6X750; ties are sold in packs of 100 at $1.91/pack.

Oxygen/Carbon Dioxide Gas Sampling Meter

This handheld instrument has a rechargeable battery that lasts up to 16 hours. It has an oxygen and carbon dioxide range of 0 percent to 25 percent. The meter has an analog scale readout with audible and visual alarms for low and high warning levels. The meter analyzes oxygen content through an electrochemical cell and carbon dioxide through an infrared sensor. An external filter and an internal filter are employed for high reliability and preventive maintenance. An internal diaphragm pump is provided.

The gas sampling meter is used to determine the oxygen and carbon dioxide content of the ambient air or of the gas within the soil. Calibrations must be performed regularly with gas standards.

The meter is sold by Cascade Associates in Youngstown, Ohio, 216 758-6649. It costs approximately $3,200.

Carry Case for Gas Sampling Meter

The case is of heavy plastic construction with foam cushioning inside and can be secured with locks.

It is capable of protecting and carrying both the Trace-Techtor and the gas sampling meter.

The case is sold by Cascade Associates in Youngstown, Ohio, 216 758-6649. It costs approximately $250.

Combustibles Sampling Meter

This meter has a digital display screen with audible and visual alarms for high- and low-level combustibles/hydrocarbons. They are measured from 0 percent to 100 percent lower explosive limit (LEL) and 0 ppm to 10,000 ppm in 20-ppm increments. The meter uses both internal and external filters and includes an internal pump. In addition, it has a data logging function, which allows the meter to be connected with an IBM-compatible computer. It can be operated with alkaline or nicad batteries that hold a 9-hour charge. The platinum catalyst sensor has a flame arrestor.

The meter is used to determine the level of hydrocarbons or combustibles in the ambient air or sampled soil gas. It is a new model that replaces the Trace-Techtor meter.

The meter is sold by Cascade Associates in Youngstown, Ohio, 216 758-6649. It costs approximately $1,475.

1:1 Diluter

The diluter is an external fitting that attaches to the inlet of the Trace-Techtor meter. It has a metal construction and is about 3 in. long. A diluter is required when the oxygen levels of the gas sample drop below 12 percent. At this low oxygen level, the platinum catalyst cannot combust the gas sample properly.

The function of the 1:1 diluter is to reduce the gas sample flow by one-half. This dilution reduces the concentration by one-half. Once a concentration reading is obtained from the meter, it is multiplied by a factor of two to compensate for the dilution.

The diluter is sold by Cascade Associates in Youngstown, Ohio, 216 758-6649. It costs approximately $150.

10:1 Diluter

This diluter is also an external fitting that attaches to the inlet of the Trace-Techtor meter and is small enough to hold in the hand. The diluter has two rotameters built into it to permit a dilution factor up to 10. A diluter is required when the oxygen levels of the gas sample drop below 12 percent. At this low oxygen level, the platinum catalyst cannot combust the gas sample properly. The 10:1 diluter can be used if the concentration of the sample is still too high to be read after using a 1:1 diluter. This is evident when the gas analysis instrument is pegged on its highest setting.

The function of the 10:1 diluter is to reduce the gas sample flow up to a factor of 10. The dilution factor is set by adjusting the two rotameters until the ratio of the two flows is equal to the dilution ratio. This reduces the concentration by the same factor. Once a concentration reading is obtained from the meter, it is multiplied by the ratio to compensate for the dilution.

The diluter is sold by Cascade Associates in Youngstown, Ohio, 216 758-6649. It costs approximately $250.

Trace-Techtor Meter

This handheld instrument has a rechargeable battery that lasts for 10 hours. It can measure petroleum-based hydrocarbon vapors (BTEX) up to 10,000 ppm. It has an analog scale readout with audible and visual alarms for low and high concentration levels. The meter analyzes the vapor through an electrochemical cell with a platinum catalyst. An external filter and an internal filter are employed for preventive maintenance and high reliability. An internal diaphragm pump is also supplied.

The gas sampling meter is used to determine the petroleum hydrocarbon content of the ambient air or of the gas within the soil. Calibrations must be performed regularly with hexane. The instrument can also be equipped to detect methane or natural gas.

The meter was sold and manufactured by GasTech in Newark, California, 415 794-1973. The price was approximately $1,500. The Trace-Techtor is no longer manufactured, however.

Interface Probe

It is constructed in the shape of a disk, which stores a 100-ft measuring tape and a sensor probe. It weighs 16 lb, is 16x18x6 in., and is battery operated. The interface probe resembles a common tape measure, only larger.

The interface probe is very useful when used alone with soil gas probes during site investigation. The probe is used in wells to detect the level at which both oil and water are present. This is accomplished through the use of audible alarms. The probe can detect an oil layer as thin as 0.05 ft.

The interface probe is made by ORS Environmental Systems in Greenville, New Hampshire, 800 228-2310. It costs approximately $2,000.

150-Ft Tape Measure

A 150-ft fiberglass reel tape is needed for site mapping during soil gas survey and is also used when measuring borehole depths and monitoring point construction.

It is available from Grainger. The catalog number is 6C192, and the cost is $57.70.

Soil Gas Probes and Well Points (The Macho System)

These are electric-powered sampling systems for driving soil gas probes. The deluxe system includes a variable-speed hammer drill and the capability to sample soil gas to a depth of approximately 10 ft. This is a good starter set; however, additional shafts, slotted well points, and hollow probe nipples are also recommended. The system is available from KVA Analytical

Systems in Falmouth, Massachusetts, 508 540-0561. The Macho System costs approximately $3,065.

Bulkhead Quick Coupler (Parker)

These brass fittings are threaded into the top of the soil gas probe after driving to the desired depth. The fitting gives the sampler an airtight connection between the probe and the vacuum sampling pump, which pulls the soil gas sample from the soil. The coupler is sold by Forberg Scientific in Columbus, Ohio, 800 209-9575.

Diaphragm Pump (Vacuum/Air Compressor)

The pumps are usually wired for 110 volts for the 1/16-hp, 1/8-hp, and 1/3-hp versions. Gast produces pumps and compressors that are preferred because of their reliability and easy maintenance.

The pumps are used to draw soil gas from deep monitoring points and soil gas probes. We recommend the 1/3-hp pump because of the available air produced at 20 psi.

The pump is sold by Grainger in Columbus, Ohio, 800 323-0620. The cost depends on the size of the pump; for the 1/3-hp pump, the catalog number is 4Z024, and the cost is $228.

Probe Puller Adapter

The probe puller adaptor was made by Battelle staff. It is a piece of square steel tubing approximately 4x4x2 in. wide. A solid probe nipple is then welded in the middle of one outside edge. The adaptor is threaded onto the top of a soil gas probe when sampling is completed. A large utility jack is placed inside the square tube, and the probe is removed.

Utility Jack

The utility jack is used for removing soil gas probes when sampling is completed. The jack is sold by Grainger, Columbus, Ohio, 800 323-0620. The catalog number is 5Z156, and the cost is $100.

Miscellaneous Supplies for Soil Gas Survey

Miscellaneous supplies include work gloves, safety glasses, small measuring tape, crescent wrenches, pipe wrenches, vise grips, field record book, cleaning supplies for cleaning soil gas probes, razor blades (single edge), electrical tape, electrical extension cords, oil, and fuel for the generator.

B.2 Vent Well Installation Equipment

Contracted Drilling Services

If a contract driller is installing the vent well and soil gas monitoring points, the driller provides monitoring vent well and well construction materials (sand and bentonite); however, the soil gas monitoring points need to be furnished to the driller. If a contract driller is not used, then items in this section will be necessary.

Hand Augering and Soil Sampling Equipment

A vent well can be installed by hard augering if soil conditions permit. The following is a list of hard augering equipment and equipment needed for collecting soils for laboratory analysis.

Auger Head

It is constructed of stainless steel to resist corrosion and contamination of soil samples. The head is approximately 1 ft long and is open on both ends to accommodate a soil sample liner. The bottom of the head is flared to allow easy penetration into the ground, while the top has a single bar with a male pipe thread. The male pipe thread attaches to the auger's extension rods.

The auger head is used to house the liner while the soil is being sampled. It is designed to sample the soil with minimal disturbance and effort.

The auger head is supplied by Enviro-Tech Services in Martinez, California, 800 468-8921. It costs approximately $85.

Core Sampler With Slide Hammer

The core sampler is a metal pole with a soil sampler at one end. On the other end is the slide hammer, a weight that slides up and down the pole of the core sampler.

The core sampler is another way to obtain undisturbed soil samples. The slide hammer drives the sampler into the ground and eliminates the need for the auger head.

The items are supplied by Enviro-Tech Services in Martinez, California, 800 468-8921. They cost approximately $225.

Sampling Extensions, Extension Cross Handle, and Carry Case

The sampling extensions are long, metal poles that connect the auger head to the cross handle with threaded ends.

The extension cross handle is placed at the top of the auger and is used for leverage to turn the auger into the ground. It may have a rubber handle for increased grip.

The metal carry case is about 6 ft long and 1 ft tall and holds the complete auger, disassembled. It has a foam lining for protection during travel.

The equipment is supplied by Enviro-Tech Services in Martinez, California, 800 468-8921. It costs approximately $400 for all three items.

Brass Sleeves and Plastic End Caps

The sleeve is a cylinder that is open at both ends. It comes in various diameters and lengths. The caps are orange and made from plastic to fit over each end of the sleeve after being filled with soil.

The sleeve is placed inside the auger head and used as a core sample liner. It contains the soil that is removed by the auger. The end caps are placed on each end of the sleeve after it is removed from the auger head. Brass sleeves are also used in the core sampler with slide hammer.

The sleeves and caps are supplied by Enviro-Tech Services in Martinez, California, 800 468-8921. The cost for both items is approximately $3.

PVC Well Screen

Well screen constructed of polyvinyl chloride (PVC) is flush-threaded at both ends to accommodate a threaded plug and the riser pipe or blank well casing. Screens are available in 10-, 20-, and 30-slot openings. Well screen is also available in stainless steel.

The screen is sold by Environmental Well Products Company in Dayton, Ohio, 800 777-0977. Price varies with size and length.

PVC Riser

PVC riser or blank casing is also flush-threaded and has no openings. It is merely an extension of pipe from the well screen to the ground surface. It is sold by Environmental Well Products Company or any drilling supply company.

Bentonite Chips

The chips are available in coarse grades or pellets in small sizes. Common sizes include 0.375-in. and 0.75-in. chips or pellets. They are made from dry bentonite clay and sold in 50-lb bags. The bentonite is chemically stable and can absorb large amounts of moisture.

The bentonite chips are placed around the necessary equipment within the borehole to form a seal and act as a general filler for the void space. Bentonite was selected because of its high water retention levels. It also interfaces well with Portland cement.

The bentonite is sold by Environmental Well Products Company in Dayton, Ohio, 800 777-0977. The price is approximately $10 for 50 lb.

Silica Sand

The sand contains silica powder for increased chemical stabilization. It is commonly found in the 10x20 graded form.

The silica sand is another form of packing used in well construction. The granular sand is added to boreholes around the screened interval of the vent well and soil gas monitoring points.

The sand is sold by Environmental Well Products Company in Dayton, Ohio, 800 777-0977. The price is approximately $6 for 50 lb.

Concrete Mix

The concrete requires only the addition of water and sets quickly. The concrete is readily available in large quantities throughout the country.

Concrete mix is placed around the manhole at ground level of the well. This ensures its stability during extended absences.

The concrete is sold by Environmental Well Products Company in Dayton, Ohio, 800 777-0977. The price is approximately $4 for 50 lb. It is also available at most building supply stores and hardware stores.

Manhole (Flushmount Well Cover)

Many companies manufacture manholes, some with bolts to secure the top. They are usually sold in 8x12-in. or 12x12-in. sizes and are made of iron, steel, or stainless steel. The bottom is designed to fit over the riser pipe or soil gas monitoring points.

The manhole serves as a marker and gives added protection to the well and the monitoring points.

The manhole is sold by Environmental Well Products Company in Dayton, Ohio, 800 777-0977. The price is approximately $50.

B.3 Soil Gas Monitoring Point Equipment

Contracted Drilling Services

If a contract driller is installing the vent well and soil gas monitoring points, the driller provides monitoring vent well and well construction materials (sand and bentonite); however, the soil gas monitoring points need to be furnished to the driller. If a contract driller is not used, then items in this section will be necessary.

Hand Augering and Soil Sampling

A vent well can be installed by hand augering if soil conditions permit. The following is a list of hand augering equipment and equipment needed for collecting soils for laboratory analysis.

Auger Head

It is constructed of stainless steel to resist corrosion and contamination of soil samples. The head is approximately 1 ft long and is open on both ends to accommodate a soil sample liner. The bottom of the head is flared to allow easy penetration into the ground, while the top has a single bar with a male pipe thread. The male pipe thread attaches to the auger's extension rods.

The auger head is used to house the liner while the soil is being sampled. It is designed to sample the soil with minimal disturbance and effort.

The auger head is supplied by Enviro-Tech Services in Martinez, California, 800 468-8921. It costs approximately $85.

Core Sampler With Slide Hammer

The core sampler is a metal pole with a soil sampler at one end. On the other end is the slide hammer, a weight that slides up and down the pole of the core sampler.

The core sampler is another way to obtain undisturbed soil samples. The slide hammer drives the sampler into the ground and eliminates the need for the auger head.

The items are supplied by Enviro-Tech Services in Martinez, California, 800 468-8921. They cost approximately $225.

Sampling Extensions, Extension Cross Handle, and Carry Case

The sampling extensions are long, metal poles that connect the auger head to the cross handle with threaded ends.

The extension cross handle is placed at the top of the auger and is used for leverage to turn the auger into the ground. It may have a rubber handle for increased grip.

The metal carry case is about 6 ft long and 1 ft tall and holds the complete auger, disassembled. It has a foam lining for protection during travel.

The equipment is supplied by Enviro-Tech Services in Martinez, California, 800 468-8921. The cost for all three items is approximately $400.

Brass Sleeves and Plastic End Caps

The sleeve is a cylinder that is open at both ends. It comes in various diameters and lengths. The caps are orange and made from plastic to fit over each end of the sleeve after being filled with soil.

The sleeve is placed inside the auger head and is used as a core sample liner. It contains the soil that is removed by the auger. The end caps are placed on each end of the sleeve after it is removed from the auger head. Brass sleeves are also used in the core sampler with slide hammer.

The sleeves and caps are supplied by Enviro-Tech Services in Martinez, California, 800 468-8921. The cost for both items is approximately $3.

Suction Strainer

The suction strainer resembles an oxygen diffuser used in fish tanks. It is approximately 0.75 in. in diameter and 8 in. long, constructed of a nylon frame with number 50 mesh screen to permit the flow of gases. The strainers must be tapped with 3/8-in. national pipe thread (NPT) to install the connector and nylon tubing.

The strainers are filled with aquarium gravel to ensure the complete mixture of the soil gas as it is sampled. The strainers are placed at the end of the nylon tubing and set in the monitoring wells. There, they are used to withdraw soil gas from the ground, free of dirt and particulate.

The strainer is sold by Grainger in Columbus, Ohio, 800 323-0620. It costs approximately $7.

NEWLOC Male Connector

The male pipe thread connector is made of plastic and has an opening on the end for 0.25-in. tubing. The other end has 0.375-in. male pipe thread.

The connector is used to attach the suction strainer to the nylon tubing in the monitoring wells.

The connector is supplied by New Age Industries in Willow Grove, Pennsylvania, 215 657-3151. It costs approximately $1.60.

Nylon Tubing

Often called Nylotube, it is made from nylon and sold in various colors for identification purposes. Most common applications of the tube involve the 0.25-in. size.

The tubing transports gases from monitoring points to the surface for soil gas sampling and can be used on some pieces of field equipment for similar purposes. This type of tubing is favorable because it is inexpensive, is chemically resistant to hydrocarbons, and is available in many colors. The tubing will adsorb some small amount of hydrocarbons, however.

The tubing is supplied by New Age Industries in Willow Grove, Pennsylvania, 215 657-3151. It costs approximately $0.36 per ft and is sold in 100-ft rolls.

Quick Connectors (Parker)

Male and female quick connectors and quick connector plugs are compatible with different tube sizes. They are made of brass or stainless steel. The quick connectors offer easy access to monitoring points for taking soil gas samples.

The quick connectors are attached to tubing when quick and convenient access is desired. They also are installed on gas sampling instruments and on tubing found at the monitoring wells. In addition, they provide a strong seal to prevent leaking. The quick connector solid plugs are placed in the female quick connectors to prevent corrosion and other forms of damage.

The connectors are sold by Forberg Scientific in Columbus, Ohio, 614 294-4600. The price for the male connector is approximately $6, and the female is approximately $11.

Thermocouple Cable, K Type

The thermocouple cable is a 24-gauge wire insulated with PVC. It can withstand temperatures up to 105°C. It is usually sold by the foot.

The thermocouple is responsible for measuring temperatures, often within a soil gas monitoring point or an outlet stream from a piece of field equipment. The cable transmits the temperature through a current and is recorded using an electronic thermometer.

The cable is supplied by Cole-Parmer in Niles, Illinois, 800 323-4340. It costs approximately $0.80 per foot.

Thermocouple Minimale Plug

The type K minimale plug has two different prongs and is attached to the thermocouple cable. It acts as a cable termination. It is slightly smaller than a normal electrical plug but serves the same purpose.

The plug is used to connect the thermocouple to the electronic thermometer for data collection of temperatures.

The plug is supplied by Cole-Parmer in Niles, Illinois, 800 323-4340. It costs approximately $5.

Brass Tags

The tags are available in 1-in. to 2-in. sizes and in either square or round shape. They are usually constructed of 19-gauge brass. The tags can be purchased with or without labeling.

The tags are stamped, if unlabeled, using a kit and are then placed on wells for identification purposes. They may also be used to label items such as pipes and valves.

The brass tags are manufactured by Seton Identification in New Haven, Connecticut, 800 754-7360. They are sold in packages of 25, for approximately $20 per package.

Tag Stamping Kit

Stamping kits are sold in sizes from 0.125 in. to 0.5 in. They contain numbers and letters made from steel.

A hammer or mallet is used to stamp the tags with the kit for custom identification.

The stamping kit is manufactured by Seton Identification in New Haven, Connecticut, 800 754-7360. The kit costs approximately $80.

Bentonite Chips

The chips are available in coarse grades or pellets in small sizes. Common sizes include 0.375-in. and 0.75-in. chips or pellets. They are made from dry bentonite clay and sold in 50-lb bags. The bentonite is chemically stable and can absorb large amounts of moisture.

The bentonite chips are placed around the necessary equipment within the borehole to form a seal and act as a general filler for the void space. Bentonite was selected because of its high water retention levels. It also interfaces well with Portland cement.

The bentonite is sold by Environmental Well Products Company in Dayton, Ohio, 800 777-0977. The price is approximately $10 for 50 lb.

Silica Sand

The sand contains silica powder for increased chemical stabilization. It is commonly found in the 10x20 graded form.

The silica sand is another form of packing used in well construction. The granular sand is added to boreholes around the screened interval of the vent well and soil gas monitoring points.

The sand is sold by Environmental Well Products Company in Dayton, Ohio, 800 777-0977. The price is approximately $6 for 50 lb.

Concrete Mix

The concrete requires only the addition of water and sets quickly. The concrete is readily available in large quantities throughout the country.

Concrete mix is placed around the manhole at the ground level of the well. This ensures its stability during extended absences.

The concrete is sold by Environmental Well Products Company in Dayton, Ohio, 800 777-0977. The price is approximately $4 for 50 lb. It is also available at most building supply stores and hardware stores.

Manhole (Flushmount Well Cover)

Many companies manufacture manholes, some with bolts to secure the top. They are usually sold in 8x12-in. or 12x12-in. sizes and are made of iron, steel, or stainless steel. The bottom is designed to fit over the riser pipe or soil gas monitoring points.

The manhole serves as a marker and gives added protection to the well and the monitoring points.

The manhole is sold by Environmental Well Products Company in Dayton, Ohio, 800 777-0977. The price is approximately $50.

150-Ft Tape Measure

A 150-ft fiberglass reel tape is needed for site mapping and measuring borehole depths and during monitoring point sand and bentonite additions.

It is sold by Grainger in Columbus, Ohio, 800 323-0620. The catalog number is 6C192, and the cost is $57.70.

Miscellaneous

Cable ties and electrical tape are useful for securing thermocouple wires and nylon tubes together before placing in open boreholes.

B.4 Air Permeability Test Equipment

Portable Generator

Several brands are available, and one with a maximum of 5,500 watts is recommended. They may be available with wheeled carts. Most have single-phase power available in the two voltage ranges. Most smaller generators run on gasoline, while the larger have diesel engines.

A portable generator is essential in a field operation where electrical access is limited. It can power equipment such as external lighting, pumps, and power tools.

The generator is sold by Grainger in Columbus, Ohio, 800 323-0620. It costs approximately $2,200.

Blowers

Gast manufactures the recommended blowers. They are oilless regenerative blowers that have a mounted motor. The motors are equipped for different voltage requirements.

The blowers are used during the injection or extraction of air at a monitoring site. They should be equipped with explosion-proof circuitry and mufflers where flammable contamination exists.

The blower is sold by Isaacs in Columbus, Ohio, 614 885-8540. Blower costs vary according to size and power. For example, a 2-hp, 145-cfm open flow blower costs $1,100.

Rotameters/Flow Meters

Rotameters are transparent flow meters with the ability to regulate flow. The tubes may be constructed from plastic or glass. Each end has a female pipe thread made from brass or plastic. The rotameters are available for various liquid and gas flow levels. Both must be installed in a vertical position for accurate readings.

The rotameter is designed to control the gas or liquid flow rate. A flow meter indicates only the rate at which liquid or gas is flowing.

The rotameter and flow meter are manufactured and sold by King Instrument Company in Huntington Beach, California, 714 841-3663. The prices vary by type but are generally $100 to $200.

Fluke Thermocouple Thermometer

This handheld, electronic instrument is the size of a large calculator and has a digital readout with an accuracy of 0.1 percent. It operates on a 9-volt battery and has two ports for type K, minimale plugs. The thermometer has dual-point and differential capability.

The Fluke thermometer is used to record temperature data from the thermocouples.

It is supplied by several companies, including Grainger in Columbus, Ohio, 800 323-0620. It costs approximately $200.

Dwyer Magnehelic Gauges

Magnehelic gauges are used for recording negative or positive pressure changes over time during the air permeability test. Four gauges mounted in a panel stand or board should be plumbed in series to cover a wide range of pressures. They are sold by Grainger in Columbus, Ohio, 800 323-0620. Catalog numbers are 3T314, 3T317, 3T319, and 3T321, and the cost is approximately $51 per gauge.

Five-Way Valves (Swagelok)

The five-way valve is installed on the magnehelic gauge panel, which gives the sampler the ability to record pressures from three points, one after another, simply by turning the valve handle. The valve is sold by Scioto Valve, 614 891-2617. The part number is B-43ZF2, and the cost is approximately $90.

Male Nonvalved Quick Couple Plug (Parker)

The fitting is connected to tubing from the five-way valve. This plug plugs into the fitting, which is attached to a soil gas monitoring point for measuring pressure during the test. It is supplied by Forberg Scientific in Columbus, Ohio, 614 294-4600. The part number is 4Z-Q4P-B, and the cost is $6.

Stopwatches

A stopwatch is necessary for each sampler who is recording pressures at a soil gas monitoring well. Pressures are recorded over time during the air permeability test. Stopwatches can be purchased at most sporting good stores or at Radio Shack. The cost is about $20.

B.5 In Situ Respiration Test Equipment

Portable Generator

Several brands are available, and one with a maximum of 5,500 watts is recommended. They may be available with wheeled carts. Most have single-phase power available in the two voltage ranges. Most smaller generators run on gasoline, while the larger have diesel engines.

A portable generator is essential in a field operation where electrical access is limited. It can power equipment such as external lighting, pumps, and power tools.

The generator is sold by Grainger in Columbus, Ohio, 800 323-0620. It costs approximately $2,200.

Diaphragm Pump (Vacuum/Air Compressor)

The pumps are usually wired for 110 volts for the 1/16-hp, 1/8-hp, and 1/3-hp versions. Gast produces the pumps and compressors. They are preferred because of their reliability and easy maintenance.

The pumps are used to draw soil gas from deep monitoring points and soil gas probes. The 1/3-hp pumps are recommended because of the available air produced at 20 psi.

The pump is sold by Grainger in Columbus, Ohio, 800 323-0620. The cost depends on the size of the pump. For the recommended 1/3-hp pump, the catalog number is 4Z024, and the cost is $228.

Rotameters/Flow Meters

Rotameters are transparent flow meters with the ability to regulate flow. The tubes may be constructed from plastic or glass. Each end has a female pipe thread made from brass or plastic.

The rotameters indicate the rate at which gas is flowing. The flow meter used for in situ respiration testing is connected to the backside of a 1/3-hp diaphragm pump.

The flow meter normally used is a 0.4-scfm to 4.0-scfm meter sold by King Instruments Company, 714 841-3663. The cost is approximately $48.

Helium Leak Detector

The helium leak detector is a rechargeable instrument that can detect helium from 0.01 percent to 100 percent. It operates in a three-stage process where the sample enters the portable instrument, is analyzed, then is purged to the atmosphere. The helium leak detector is approximately 14x12x5 in. and weighs 7 lb. The instrument must be calibrated with helium gas.

The helium leak detector is used to detect the presence of helium. Helium gas is injected into the ground during a tracer test. From this test, an underground model of the gas dispersion can be developed. The detector analyzes soil gas samples from the monitoring wells surrounding the helium injection site.

The leak detector is sold by Mark Products, Incorporated, in Sunnyvale, California, 800 621-4600. The price is approximately $4,500.

Compressed Gas Helium 220 Ft^3

Helium is mixed with the injection air for the in situ respiration test at approximately 2-percent helium. Helium can be purchased from compressed gas suppliers or a welding supplier. The cost per cylinder is $60.

Helium Cylinder Regulator

A two-stage cylinder regulator is necessary for connecting and dispensing the compressed helium gas. The correct connection for cylinder to regulator is a GA 580. Regulators can be purchased through the compressed gas supplier. The cost is approximately $180.

Helium/Air Mixing Manifold

The 2-percent helium mix in air is accomplished by using a 1-in. inside diameter pipe closed at one end with four tubing connectors, which would be plumbed to the diaphragm pumps. The open end of the pipe is where atmospheric air is drawn in for the diaphragm pumps; a tubing connection is installed into the pipe at about 6 in. from the open end. This connection is for the helium supply to enter the manifold and be swept by incoming air. Helium concentrations need to be measured at the pressure side of the diaphragm pump; if concentration is too high or low, adjust at the helium regulator. This item is not commercially available.

Calibration Gases

Calibration gases include helium, carbon dioxide, oxygen, and hexane. They are available in the appropriate concentrations for each instrument and may require a special regulator depending on the cylinder type.

The calibration gases are used to standardize the gas analyzing instruments.

The gases are sold through Scott Specialty Gases in Troy, Michigan, 313 589-2950. The gases cost approximately $124 depending on the cylinder size and gas desired.

Tedlar Sampling Bag

The 1-L bag is made from transparent Tedlar and has a polypropylene fitting. The bag is approximately 7x7 in. and is sold in packages of 10. The fitting is opened and closed by twisting the cap, which can also be locked into place.

The Tedlar bag is used to store soil gas samples and calibration gases until they can be analyzed by an appropriate gas meter.

The Tedlar bags are supplied by SKC, Eighty Four, Pennsylvania, 800 752-8472. The cost is approximately $82 for 10 bags.

Fluke Thermocouple Thermometer

This handheld, electronic instrument is the size of a large calculator and has a digital readout with an accuracy of 0.1 percent. It operates on a 9-volt battery and has two ports for type K, minimale plugs. The thermometer has dual-point and differential capability.

The Fluke thermometer is used to record temperature data from the thermocouples.

The Fluke meter is supplied by several companies including Grainger in Columbus, Ohio, 800 323-0620. It costs approximately $200.

Pressure and Vacuum Gauges

Pressure gauges are installed with the flow meters for air injection. When flow is recorded, the pressure needs to be recorded as well. Vacuum gauges are used on the diaphragm pump that is used for withdrawing soil gas samples from monitoring points; the vacuum is also recorded while collecting soil gas sample. The gauges are sold by Grainger in Columbus, Ohio, 800 323-0620. The catalog number is 1A318, and the cost is less than $20 per gauge.

Oxygen/Carbon Dioxide Gas Sampling Meter

This handheld instrument has a rechargeable battery that lasts up to 16 hours. It has an oxygen and carbon dioxide range of 0 percent to 25 percent. The meter has an analog scale readout with audible and visual alarms for low and high warning levels. The meter analyzes oxygen content through an electrochemical cell and carbon dioxide through an infrared sensor. An external filter and an internal filter are employed for high reliability and preventive maintenance. An internal diaphragm pump is also provided.

The gas sampling meter is used to determine the oxygen and carbon dioxide content of the ambient air or of the gas within the soil. Calibrations must be performed regularly with gas standards.

The meter is sold by Cascade Associates in Youngstown, Ohio, 216 758-6649. It costs approximately $3,200.

Carry Case for Gas Sampling Meter

The case is of heavy plastic construction with foam cushioning inside and can be secured with locks.

It is capable of protecting and carrying both the Trace-Techtor and the gas sampling meter.

The case is sold by Cascade Associates in Youngstown, Ohio, 216 758-6649. It costs approximately $250.

Combustibles Sampling Meter

This meter has a digital display screen with audible and visual alarms for high- and low-level combustibles/hydrocarbons. They are measured from 0 percent to 100 percent LEL and 0 ppm to 10,000 ppm in 20-ppm increments. The meter uses both internal and external filters and includes an internal pump. In addition, it has a data logging function, which permits the meter to be connected with an IBM-compatible computer. It can be operated with alkaline or nicad batteries that hold a 9-hour charge. The platinum catalyst sensor has a flame arrestor.

The meter is used to determine the level of hydrocarbons or combustibles in the ambient air or sampled soil gas. It is a new model that replaces the Trace-Techtor meter.

The meter is sold by Cascade Associates in Youngstown, Ohio, 216 758-6649. It costs approximately $1,475. For information on other distributors of GasTech Instruments, call GasTech at 510 794-6200.

1:1 Diluter

The diluter is an external fitting that attaches to the inlet of the Trace-Techtor meter. It has a metal construction and is about 3-in. long. A diluter is required when the oxygen levels of the gas sample drop below 12 percent. At this low oxygen level, the platinum catalyst cannot combust the gas sample properly.

The function of the 1:1 diluter is to reduce the gas sample flow by one-half. This dilution reduces the concentration by one-half. Once a concentration reading is obtained from the meter, it is multiplied by a factor of two to compensate for the dilution.

The diluter is sold by Cascade Associates in Youngstown, Ohio, 216 758-6649. It costs approximately $150.

10:1 Diluter

This diluter is also an external fitting that attaches to the inlet of the Trace-Techtor meter and is small enough to hold in the hand. The diluter has two rotameters built into it to permit a dilution factor up to 10. A diluter is required when the oxygen levels of the gas sample drop below 12 percent. At this low oxygen level, the platinum catalyst cannot combust the gas sample properly. The 10:1 diluter can be used if the concentration of the sample is still too high to be read after using a 1:1 diluter. This is evident when the gas analysis instrument is pegged on its highest setting.

The function of the 10:1 diluter is to reduce the gas sample flow up to a factor of 10. The dilution factor is set by adjusting the two rotameters until the ratio of the two flows is equal to the dilution ratio. This reduces the concentration by the same factor. Once a concentration reading is obtained from the meter, it is multiplied by the ratio to compensate for the dilution.

The diluter is sold by Cascade Associates in Youngstown, Ohio, 216 758-6649. It costs approximately $250.

B.6 Miscellaneous Items

Teflon Thread Tape

The white tape is made of Teflon and comes in rolls of 0.25-in., 0.5-in., and 1-in. widths.

The tape is wrapped over pipe threading to prevent leaking of liquids and gases.

The tape is supplied by U.S. Plastics Corporation in Lima, Ohio, 800 357-9724. It costs approximately $1.

PVC Piping Supplies

PVC pipe is needed in various diameters up to 6 in. Most piping used is schedule 40 and in 10-ft or 20-ft lengths. Some of the supplies, including valves, tees, and couplings, may be needed as schedule 80 PVC.

The PVC piping is used to transport gases, usually air, to vent wells or to transport liquids from contaminated wells.

The items are supplied by U.S. Plastics Corporation in Lima, Ohio, 800 357-9724. The costs are dependent upon the specific piping size, length, and schedule required.

PVC Pipe Cement and Primer

The PVC primer is a volatile, clear liquid that is applied using a small sponge. The PVC cement is a viscous, gray liquid also applied with a sponge. Both have a strong odor that can be harmful if the primer is used without proper ventilation.

The primer is used to clean and prime the PVC before assembly. After the primer dries, the cement is applied to connect the PVC pieces. The PVC cement is quick to set.

The items are supplied by U.S. Plastics Corporation in Lima, Ohio, 800 357-9724. For both the cement and primer, the cost is approximately $20.

Pipe Fittings

Many different types and sizes of pipe fitting are needed for pump connections and tubing connections. Grainger has a large selection in its catalog of steel and brass pipe fittings that are reasonably priced.

B.7 Optional Items

Soil Moisture Meter

The soil moisture meter is an electronic, handheld instrument that operates from a 9-volt battery. Two spring terminals are at the top of the meter for connecting the moisture blocks.

The meter gives a digital display of the soil moisture content in a percentage obtained from the soil moisture blocks.

The meter is supplied by Soilmoisture Equipment Corporation in Santa Barbara, California, 805 964-3525. It costs approximately $310.

Soil Moisture Blocks

They consist of a lead wire connected to the gypsum block, which is in the shape of a 1-in. diameter cylinder. The blocks have a life expectancy of 3 to 5 years. The gypsum can compensate for varying salinity conditions.

The blocks are placed in the soil to transmit the soil moisture content to the soil moisture meter using an electric current. They are available in different lengths and are installed along with the soil gas monitoring points.

The block is supplied by Soilmoisture Equipment Corporation in Santa Barbara, California, 805 964-3525. It costs approximately $15.

Bailer

Constructed of Teflon, PVC, or stainless steel, the bailers are available from 1-ft to 4-ft lengths. Teflon is preferred for its chemical inert properties and low cost.

The bailers are lowered into the wells with cords or rope to remove water or other standing liquids. The well must be dry to install the screens and suction strainers. Otherwise, no soil gas sampling can occur because of the presence of the liquid(s).

The bailer is sold by Environmental Well Products Company in Dayton, Ohio, 800 777-0977. The price is approximately $140.

Appendix C
Example Procedures for Conducting Bioventing Treatability Studies

C.1 Example Procedures for Collecting, Labeling, Packing, and Shipping Soil Samples

C.1.1 Sample Collection

Soil samples are usually collected from split-spoon samplers during soil-boring operations or with handheld soil augers. Regardless of how samples are collected, all equipment must be decontaminated before and after collection of each sample.

C.1.1.1 Equipment Decontamination

- Sampler is thoroughly washed.
- Sampler is rinsed with deionized or distilled water.
- Sampler is rinsed with methanol and allowed to air dry.
- Rinsates are disposed of in an environmentally sound manner.

C.1.1.2 Sample Collection

- At a minimum, rubber or vinyl gloves should be worn to collect the sample. If higher levels of contamination are anticipated, nitrile or nitrocellulose gloves should be worn in addition to other appropriate safety gear as indicated in the site health and safety plan.
- During processing of soil samples, the work area should be covered with vinyl or plastic. Between samples, the work area should be cleaned of soil residues. The work area should be positioned upwind of the test area or drill rig.
- For split-spoon sampling, the soil core is usually retained in the stainless steel or brass sampling tube. The tube should be capped top and bottom after a Teflon liner or its equivalent has been placed over the exposed soil.
- If the soil is to be transferred to other containers such as those listed below for various analysis types, the sample should be scooped directly into the sample container. If organic analyses are to be performed, the scoop should be stainless steel. A soil core sample should be spooned or scooped directly from the container (e.g., coring tube, split spoon) into the sample container.
- If a gloved hand comes into contact with the sample, then new gloves should be used for each sample. In addition, a background sample that contacts a glove should be collected as a control.

C.1.1.3 Split Samples

A homogeneous mix for a split soil sample can be obtained by mixing soil in a stainless steel pan and filling both sample containers with alternate spoonfuls. If a sample is collected for trace volatile analysis, however, too much sample agitation and mixing can drive off the compounds of concern. Consequently, if a split spoon or other soil sample for volatile organic analysis is to be split and concern arises that the above homogenization would result in the loss of trace volatile compounds, an alternate splitting technique should be used. The undisturbed core or soil should be spooned directly into the two jars by alternating spoonfuls between the sample and the split container. This ensures a fairly even split while reducing the agitation and exposure of the sample surface area.

C.1.1.4 Sample Containers and Sample Size

Soil samples should be stored in appropriate containers as indicated in the site test plant or as directed by the analytical laboratory. For sample size requirements, refer to the site test plan or ask personnel in the analytical laboratory. Some suggested container types and sample sizes include:

- *Volatiles:* Glass jar, wide mouth, Teflon-faced cap, 125-mL capacity, 100-g sample volume minimum.
- *Semivolatiles:* Glass jar, wide mouth, Teflon-faced cap, 125-mL capacity, 100-g sample volume minimum.
- *Metals:* High-density polyethylene (HDPE) or glass wide-mouth jar.
- *Other:* For other soil analysis types, including particle-size analysis, nutrient analysis, and moisture determination, samples can be stored in metal, plastic, or glass containers.

C.1.2 Sample Label and Log

A sample must be labeled with all information that would be required by personnel working with the sample. Refer to the test/project plan for labeling instructions. At a minimum, the samples should be labeled with the following information:

- Test site where sample was collected.
- Soil boring number or identification number.
- Soil sampling depth.
- Initials of sampler.
- Date and time of collection.
- Information to be recorded in the log/record book: specific equipment used, sampler, date and time, and any observations about the sampled material or meter readings taken.

C.1.3 Sample Packing and Shipping

- The soil samples should be placed in plastic bags and put in a refrigerator, ice chest, or insulated box on ice immediately after being placed in an appropriate container and labeled. Ensure that sample containers and bags are tightly closed and that they contain sufficient ice to maintain refrigerated conditions until samples arrive at the laboratory.
- Control samples and field blanks should not be shipped with contaminated samples.
- Chain-of-custody forms should be completed for each cooler.
- Samples should be shipped to arrive within 24 hours whenever possible. Shipment should be made by Federal Express (when possible), using Priority Overnight Service with Saturday deliveries specified if applicable.
- Recipients should be notified about specifics of shipment.

C.1.4 Quality Control

- Descriptions and dates of all of the above activities should be documented in study records.
- Soil analysis information should be included in the study records. Photographs should be taken periodically and retained with the study records.
- Records should be kept as indicated in this procedure and should be periodically reviewed by the study/task leader.

C.2 Example Procedures for in Situ Respiration Testing

C.2.1 Field Instrumentation and Measurement

C.2.1.1 Oxygen and Carbon Dioxide

Gaseous concentrations of carbon dioxide and oxygen should be analyzed using a GasTech model 3252OX carbon dioxide/oxygen analyzer or equivalent. The battery charge level should be checked to ensure proper operation. The air filters should be checked and, if necessary, cleaned or replaced before starting the experiment. The instrument should be turned on and equilibrated for at least 30 minutes before conducting calibration or obtaining measurements. The sampling pump of the instrument should be checked to ensure that it is functioning properly. Low flow of the sampling pump may indicate that the battery level is low or that some fines are trapped in the pump or tubing.

Each day before use, meters should be calibrated against purchased carbon dioxide and oxygen calibration standards. These standards should be in the concentration range of the soil gas to be sampled. The carbon dioxide calibration should be performed against atmospheric carbon dioxide (0.05 percent) and a 5 percent standard. The oxygen should be calibrated using atmospheric oxygen (20.9 percent) and against a 5 percent and 0 percent standard. Standard gases should be purchased from a specialty gas supplier. To calibrate the instrument with standard gases, a Tedlar bag (capacity approximately 1 L) should be filled with the standard gas and the valve on the bag should be closed. The inlet nozzle of the instrument should be connected to the Tedlar bag, and the valve on the bag should be opened. The instrument should then be calibrated against the standard gas according to the manufacturer's instructions. Next, the inlet nozzle of the instrument should be disconnected from the Tedlar bag, and the valve on the bag should be shut off. The instrument should be rechecked against atmospheric concentration. If recalibration is required, the above steps should be repeated.

C.2.1.2 Hydrocarbon Concentration

Petroleum hydrocarbon concentrations should be analyzed using a GasTech Trace-Techtor hydrocarbon analyzer (or equivalent) with range settings of 100 ppm, 1,000 ppm, and 10,000 ppm. The analyzer should be calibrated against two hexane calibration gases (500 ppm and 4,400 ppm). The Trace-Techtor has a dilution fitting that can be used to calibrate the instrument in the low-concentration range.

Calibration of the GasTech Trace-Techtor is similar to the GasTech Model 32402X, except that a mylar bag is used instead of a Tedlar bag. The oxygen concentration must be above 10 percent for the Trace-Techtor analyzer to be accurate. When the oxygen drops below 10 percent, a dilution fitting must be added to provide adequate oxygen for analysis.

Hydrocarbon concentrations can also be determined with a flame ionization detector (FID), which can detect low (below 100 ppm) concentrations. A photoionization detector (PID) is not acceptable.

C.2.1.3 Helium Monitoring

Helium in the soil gas should be measured with a Marks Helium Detector Model 9821 or equivalent with a minimum sensitivity of 100 ppm (0.01 percent). Calibration of the helium detector follows the same basic procedure described for oxygen calibration, except that the setup for calibration is different. Helium standards used are 100 ppm (0.01 percent), 5,000 ppm (0.5 percent), and 10,000 ppm (1 percent).

C.2.1.4 Temperature Monitoring

In situ soil temperature should be monitored using Omega Type J or K thermocouples (or equivalent). The thermocouples should be connected to an Omega OM-400 Thermocouple Thermometer (or equivalent). The contractor should calibrate each thermocouple against ice water and boiling water before field installation.

C.2.1.5 Air Flow Measurement

Before initiating respiration tests at individual monitoring points, air should be pumped into each monitoring point using a small air compressor. Air flow rates of 1 cfm to 1.5 cfm should be used, and flow should be measured using a Cole-Palmer Variable Area Flowmeter No. N03291-4 (or equivalent). Helium should be introduced into the injected air at a 1 percent concentration. A helium flow rate of approximately 0.01 cfm to 0.015 cfm (0.6 cfm to 1.0 cfh) is required to achieve this concentration. A Cole-Palmer Model L-03291-00 flow meter or equivalent should be used to measure the flow rate of the helium feed stream.

C.2.2 In Situ Respiration Test Procedures

The in situ respiration test should be conducted using a minimum of four screened intervals of the monitoring points and a background well. The results from this test determine if in situ microbial activity is occurring and if it is oxygen-limited.

C.2.2.1 Test Implementation

Air with 1 percent to 2 percent helium should be injected into the monitoring points and background well. Following injection, the change of oxygen, carbon dioxide, total hydrocarbon, and helium in the soil gas should be measured over time. Helium should be used as an inert tracer gas to assess the extent of diffusion of soil gases within the aerated zone. If the background well is screened over an interval of greater than 10 ft, the required air injection rate may be too high to allow helium injection. The background monitoring point should be used to monitor natural degradation of organic matter in the soil.

The oxygen, carbon dioxide, and total hydrocarbon levels will be measured at the monitoring points before air injection. Normally, air is injected into the ground for at least 20 hours at rates ranging from 1.0 cfm to 1.7 cfm (60 cfh to 100 cfh). Blowers should be diaphragm compressors Model 4Z024 from Grainger (or equivalent) with a nominal capacity of 1.7 cfm (100 cfh) at 10 psi. The helium used as a tracer should be 99 percent or greater purity, which is available from most welding supply stores. The flow rate of helium should be adjusted to 0.6 cfh to 1.0 cfh to obtain about 1 percent in the final air mixture that is injected into the contaminated area. Helium in the soil gas should be measured with a Marks Helium Detector Model 9821 (or equivalent) with a minimum sensitivity of 0.01 percent.

After air and helium injection is completed, the soil gas should be measured for oxygen, carbon dioxide, helium, and total hydrocarbon. Soil gas should be extracted from the contaminated area with a soil gas sampling pump system. Typically, measurement of the soil gas should be conducted after 2, 4, 6, and 8 hours and then every 4 to 12 hours, depending on the rate of the oxygen use. If oxygen uptake is rapid, more frequent monitoring is required. If it is slower, less frequent readings are acceptable.

At shallow monitoring points, atmospheric air might be pulled in during purging and sampling. Excessive purging and sampling may result in erroneous readings. Oversampling offers no benefits, so care should be taken to minimize the volume of air extraction when sampling shallow points. In these cases, a low-flow extraction pump of about 0.03 cfm to 0.07 cfm (2.0 cfh to 4.0 cfh) should be used. Field judgment is required at each site in determining the sampling frequency.

The in situ respiration test should be terminated when the oxygen level is about 5 percent, or after 5 days of sampling. The temperature of the soil before air injection and after the in situ respiration test should be recorded.

C.2.2.2 Data Interpretation

Data from the in situ respiration tests should be summarized and their oxygen utilization rates computed.

C.2.3 Quality Control

- Descriptions and dates of all of the above activities should be documented in study records.

- Soil analysis information should be included in the study records. Photographs should be taken periodically and retained with the study records.
- Records should be kept as indicated in this procedure and should be periodically reviewed by the study/task leader.

C.3 Example Procedures for Soil Gas Permeability Testing

C.3.1 Field Instrumentation and Measurement

C.3.1.1 Oxygen and Carbon Dioxide

Gaseous concentrations of carbon dioxide and oxygen should be analyzed using a GasTech model 3252OX carbon dioxide/oxygen analyzer or equivalent. The battery charge level should be checked to ensure proper operation. The air filters should be checked and, if necessary, cleaned or replaced before starting the experiment. The instrument should be turned on and equilibrated for at least 30 minutes before conducting calibration or obtaining measurements. The sampling pump of the instrument should be checked to ensure that it is functioning properly. Low flow of the sampling pump can indicate that the battery level is low or that some fines are trapped in the pump or tubing.

Each day before use, meters should be calibrated against purchased carbon dioxide and oxygen calibration standards. These standards should be in the concentration range of the soil gas to be sampled. The carbon dioxide calibration should be performed against atmospheric carbon dioxide (0.05 percent) and a 5 percent standard. The oxygen should be calibrated using atmospheric oxygen (20.9 percent) and against a 5 percent and 0 percent standard. Standard gases should be purchased from a specialty gas supplier. To calibrate the instrument with standard gases, a Tedlar bag (capacity approximately 1 L) should be filled with the standard gas and the valve on the bag should be closed. The inlet nozzle of the instrument should be connected to the Tedlar bag, and the valve on the bag should be opened. The instrument should then be calibrated against the standard gas according to the manufacturer's instructions. Next, the inlet nozzle of the instrument should be disconnected from the Tedlar bag, and the valve on the bag should be shut off. The instrument should be rechecked against atmospheric concentration. If recalibration is required, the above steps should be repeated.

C.3.1.2 Hydrocarbon Concentration

Petroleum hydrocarbon concentrations should be analyzed using a GasTech Trace-Techtor hydrocarbon analyzer (or equivalent) with range settings of 100 ppm, 1,000 ppm, and 10,000 ppm. The analyzer should be calibrated against two hexane calibration gases (500 ppm and 4,400 ppm). The Trace-Techtor has a dilution fitting that can be used to calibrate the instrument in the low-concentration range.

Calibration of the GasTech Trace-Techtor is similar to the GasTech Model 32402X, except that a mylar bag is used instead of a Tedlar bag. The oxygen concentration must be above 10 percent for the Trace-Techtor analyzer to be accurate. When the oxygen drops below 10 percent, a dilution fitting must be added to provide adequate oxygen for analysis.

Hydrocarbon concentrations can also be determined with a flame ionization detector (FID), which can detect low (below 100 ppm) concentrations. A photoionization detector (PID) is not acceptable.

C.3.1.3 Pressure/Vacuum Monitoring

Changes in soil gas pressure during the air permeability test should be measured at monitoring points using Magnehelic or equivalent gauges. Tygon or equivalent tubing should be used to connect the pressure/vacuum gauge to the quick-disconnect on the top of each monitoring point. Similar gauges should be positioned before and after the blower unit to measure pressure at the blower and at the head of the venting well. Pressure gauges are available in a variety of pressure ranges, and the same gauge can be used to measure either positive or negative (vacuum) pressure by switching inlet ports. Gauges are sealed and calibrated at the factory and should be rezeroed before each test. The following pressure ranges (in inches H_2O) typically are available for this field test:

0-1”, 0-5”, 0-10”, 0-20”, 0-50”, 0-100”, and 0-200”

Air pressure during injection for the in situ respiration test should be measured using a pressure gauge with a minimum range of 0 psig to 30 psig.

C.3.1.4 Air Flow Measurement

During the air permeability test, an accurate estimate of flow (Q) entering or exiting the vent well is required to determine k and R_I. Several air flow measuring devices are acceptable for this test procedure.

Pitot tubes or orifice plates combined with an inclined manometer or differential pressure gauge are acceptable for measuring flow velocities of 1,000 ft/min or greater (approximately 20 scfm in a 2-in. pipe). For lower flow rates, a large rotameter provides a more accurate measurement. If an inclined manometer is used, the manometer must be rezeroed before and after the test to account for thermal expansion/contraction of the water. Devices to measure static and dynamic pressure must also be installed in straight pipe sections according to manufacturer's specifications. All flow rates should be corrected to standard temperature and ambient pressure (altitude) conditions.

C.3.2 Soil Gas Permeability Test Procedures

This section describes the field procedures that will be used to gather data to determine k and to estimate R_I.

Before initiating the soil gas permeability test, the site should be examined for any wells (or other structures) that will not be used in the test but may serve as vertical conduits for gas flow. These should be sealed to prevent short-circuiting and to ensure the validity of the soil gas permeability test.

C.3.2.1 System Check

Before proceeding with this test, soil gas samples should be collected from the vent well, the background well, and all monitoring points, and analyzed for oxygen, carbon dioxide, and volatile hydrocarbons. After the blower system has been connected to the vent well and the power has been hooked up, a brief system check should be performed to ensure proper operation of the blower and the pressure and air flow gauges, and to measure an initial pressure response at each monitoring point. This test is essential to ensure that the proper range of Magnehelic gauges is available for each monitoring point at the onset of the soil gas permeability test. Generally, a 10-minute to 15-minute period of air extraction or injection is sufficient to predict the magnitude of the pressure response and the ability of the blower to influence the test volume.

C.3.2.2 Soil Gas Permeability Test

After the system check, and when all monitoring point pressures have returned to zero, the soil gas permeability test should begin. Two people are required during the initial hour of this test. One person reads the Magnehelic gauges, and the other person records pressure (P') versus time on the example data sheet. Designating one person for each test improves the consistency in reading the gauges and reduces confusion. Typically, the following test sequence is followed:

1. Connect the Magnehelic gauges to the top of each monitoring point with the stopcock opened. Return the gauges to zero.
2. Turn the blower unit on, and record the starting time to the nearest second.
3. At 1-minute intervals, record the pressure at each monitoring point, beginning at $t = 60$ s.
4. After 10 minutes, extend the interval to 2 minutes. Return to the blower unit, and record the pressure reading at the well head, the temperature readings, and the flow rate from the vent well.
5. After 20 minutes, measure P' at each monitoring point in 3-minute intervals. Continue to record all blower data at 3-minute intervals during the first hour of the test.
6. Continue to record monitoring point pressure data at 3-minute intervals until the 3-minute change in P' is less than 0.1 in. of H_2O. At this time, a 5-minute to 20-minute interval can be used. Review data to ensure accurate data were collected during the first 20 minutes. If the quality of these data is in question, turn off the blower, allow all monitoring points to return to zero pressure, and restart the test.
7. Begin to measure pressure at any ground-water monitoring points that have been converted to monitoring points. Record all readings, including zero readings and the time of the measurement. Record all blower data at 30-minute intervals.
8. Once the interval of pressure data collection has increased, collect soil gas samples from monitoring points and the blower exhaust (if extraction system), and analyze for oxygen, carbon dioxide, and hydrocarbons. Continue to gather pressure data for 4 to 8 hours. The test normally continues until the outermost monitoring point with a pressure reading does not increase by more than 10 percent over a 1-hour interval.
9. Calculate the values of k and R_I with the data from the completed test; use of the HyperVentilate computer program is recommended.

C.3.2.3 Soil Gas Monitoring After the Permeability Test

Immediately after completion of the permeability test, soil gas samples should be collected from the vent well, the background well, and all monitoring points, and analyzed for oxygen, carbon dioxide, and hydrocarbons. If the oxygen concentration in the vent well has increased by 5 percent or more, oxygen and carbon dioxide should be monitored in the vent well in a manner similar to that described for the monitoring points in the in situ respiration test. (Initial monitoring may be less frequent.) The monitoring should provide additional in situ respiration data for the site.

C.3.3 Quality Control

- Descriptions and dates of all of the above activities should be documented in study records.
- Soil analysis information should be included in the study records. Photographs should be taken periodically and retained with the study records.
- Records should be kept as indicated in this procedure and should be periodically reviewed by the study/task leader.

C.4 References

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

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

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Appendix D
Off-Gas Treatment Options

D.1 Introduction

Off-gas treatment typically is not a component of bioventing systems. Bioventing systems are usually configured to inject air into the in situ soil mass. The injected air then moves through the soil to act as an oxygen source for microbial activity. The bioventing injection air flow rate is low and is selected to minimize discharge from the surface while providing an adequate supply of oxygen for the organisms.

Air injection is the preferred bioventing configuration; however, air extraction may be necessary at sites where air emissions or movement of vapors into subsurface structures are difficult to control. If a building or other structure is located within the radius of influence of a site, or if the site is near a property boundary beyond which hydrocarbon vapors cannot be pushed, air extraction may be considered. A significant disadvantage of the air extraction configuration is that biodegradation is limited to the contaminated soil because vapors do not move outward and create an expanded bioreactor. The result is less biodegradation and more volatilization. In general, increasing extraction rates increases both volatilization and biodegradation rates until the site becomes aerated. At this point, increasing the flow rate does not increase biodegradation but does continue to increase volatilization. The optimal input air flow is the minimum extraction rate that satisfies the oxygen demand. Some volatilization occurs regardless of the extraction rate. The relative removal attributed to biodegradation and volatilization is quite variable and site dependent. At a JP-4 jet fuel contaminated site at Tyndall AFB, Miller et al. (1991) found that biodegradation could achieve about 85-percent contaminant removal at the optimal air flow rate.

Currently, only 6 of 120 Bioventing Initiative sites use air extraction to oxygenate the site. Two of the sites (Davis Global Communications Site, near McClellan AFB, and BX Service Station, Patrick AFB) operated in extraction mode for 60 to 90 days, at which time the system was reconfigured for air injection because vapor concentrations had significantly decreased. At Patrick AFB, initial vapor concentrations of TPH were as high as 27,000 ppmv. After approximately 75 days of operation, concentrations decreased to 1,600 ppmv and the bioventing system was reconfigured for injection. Another site that has used extraction is the Base Service Station at Vandenberg AFB. This site contains high concentrations of the more volatile fuel components and is an active service station. As such, the possibility of vapors migrating into the building on site is possible. This bioventing system was operated in an extraction configuration in two phases (Downey et al., 1994). During Phase I, extracted soil gas was passed through a PADRE vapor treatment system, where high concentrations of volatiles were adsorbed and condensed to liquid fuel. The treated soil gas was then recirculated through the soil using air injection, biofilter trenches located along the perimeter of the site. Phase II was initiated once TVH concentrations decreased to less than 1,000 ppmv. At this time, the PADRE system was taken off-line, and the extracted soil gas was reinjected directly into the biofilter trenches.

This appendix discusses minimization of the off-gas flow rate, seven commercially available alternatives for treating organic vapors in an air stream, and some emerging vapor treatment technologies. The vapor treatment technology discussions in this appendix derive from information on remedial technologies published by AFCEE (1992 and 1994) and a description of off-gas treatment in *Soil Vapor Extraction Technology: Reference Handbook* (U.S. EPA, 1991). Figure 1 shows the general ranges of applicability for some commonly used off-gas treatment methods. The organic vapor treatment options discussed in the following sections are:

- Limiting off-gas production
- Direct discharge
- Off-gas reinjection
- Biofiltration
- Adsorption on carbon or resin
- Catalytic oxidation
- Flame incineration
- Thermal destruction in internal combustion engines
- Emerging vapor treatment technologies

Many of these methods have been used in industrial applications to control point source VOC emissions. Figure 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 only a small part of that range. For example, granular activated carbon (GAC) adsorption could be used to treat a vapor stream containing 10,000 ppmv of hydrocarbon vapors, but the cost for carbon regeneration would be prohibitive.

As shown in Figure 1, thermal treatment methods are more cost-effective for treating off-gas containing higher concentrations of vapor contaminants. No distinct guidelines exist for selecting thermal treatment units for specific applications, but the tradeoff between capital and operating costs sets general ranges of applicability for thermal treatment methods. Catalytic oxidation units usually have higher initial cost but lower fuel requirements than flame incinerators. As a result, the catalytic oxidation units are usually economical for influent containing less than 5,000 ppmv of contaminants. The capital cost of internal combustion engine (ICE) treatment units is similar to catalytic oxidation units. The ICE is not limited to operating with an inlet combustible vapor concentration below 25 percent of the lower explosive limit (LEL). The ICE units, therefore, gain a significant advantage when the vapor concentration is over 25 percent of the LEL.

D.2 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 should be used whenever possible at bioventing sites. Options for 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. Bioventing systems can be operated at much lower air flow rates than standard soil vapor extraction systems. A well-designed and operated bioventing system can minimize off-gas releases without compromising oxygenation of the contaminated area. As discussed above, air injection systems are preferred unless site conditions require air extraction to control movement or accumulation of contaminant vapors.

D.3 Direct Discharge

Direct discharge involves releasing air that contains organic vapors directly through a stack. The stack disperses the vapors, but no removal or destruction of contaminants occurs. When the organic vapor concentration in the extraction well off-gas stream is low, or in localities with less stringent air treatment standards, treatment may not be required. Direct discharge of vapors to the atmosphere can be a viable option where consistent with good environmental practice and local permitting requirements. The concentration of the contaminants, the off-gas release rate, and the location and type of nearby receptors are considered when evaluating direct discharge options.

D.4 Off-Gas Reinjection

Reinjection of off-gas for further biodegradation can be a cost-effective and environmentally sound treatment option. Off-gas reinjection configurations offer the advantages of low surface emissions and no point source

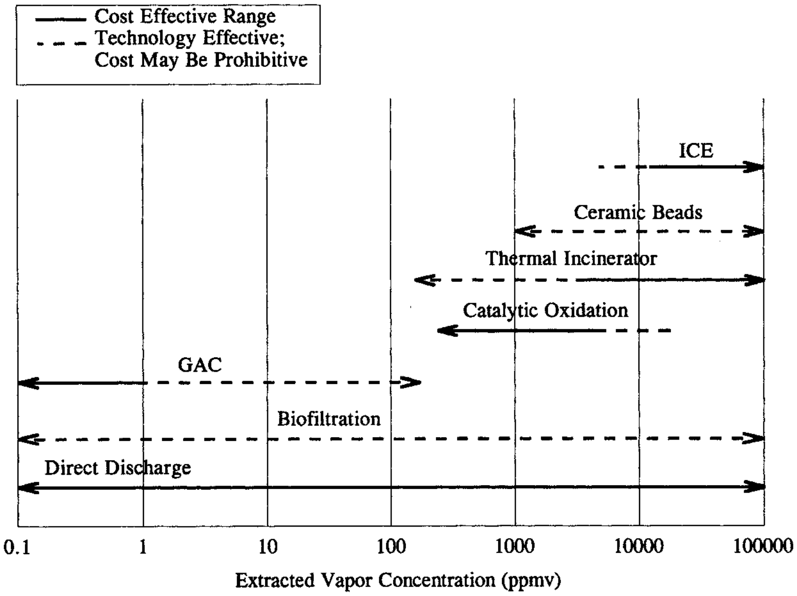

Figure 1. Applicability of vapor treatment options.

generation. The reinjection treatment option consists of distributing extracted air with contaminant vapors back into the soil to allow in situ aerobic biodegradation to destroy the contaminants. Reinjection is accomplished by piping the discharge of the extraction blowers to air distribution wells or trenches, where the air infiltrates back into the soil. In situ respiration and soil gas permeability data must be available for the site. These data indicate the expected biodegradation rate and radius of influence needed to determine the design capacity for the reinjection point. 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.

Reinjection wells should be located and designed to ensure that the reinjection process destroys contaminants rather than increasing contaminant migration. After reinjection is established, surface emission testing may be performed to ensure contaminants are not escaping at the site surface. Soil gas monitoring should be performed to ensure that contaminant migration is not being increased. Monitoring of migration is particularly important at sites where air extraction is necessary because of the presence of buildings.

D.5 Biofiltration

Biofiltration can be used to destroy a variety of volatile organic contaminants in an off-gas stream. The biofiltration process uses microorganisms immobilized as a biofilm on a porous filter substrate, 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 are metabolized. Influent contaminant concentrations less than about 1,000 ppmv can be treated with a typical contact time of 15 to 90 seconds (Skladany et al., 1994). Vendor data indicate that biofiltration is most effective for gasoline hydrocarbon vapor concentrations in the range of 50 ppmv to 5,000 ppmv (U.S. EPA, 1994).

Saberiyan et al. (1992) studied the use of a biofilter for treatment of air containing gasoline vapors. Sphagnum moss was used as the packing material. The system initially was inoculated with a hydrocarbon-degrading bacterial culture, then exposed to gasoline vapors. The biofilter removed up to 90 percent of the initial 50-ppmv gasoline vapor concentration. These studies also sought to demonstrate the linear relationship between flow rate and packing material volume.

Biofiltration of vapor streams is a fairly well-established treatment technology in Europe (Leson and Winer, 1991). Medina et al. (1995) have studied the use of biofilters to treat ethanol and gasoline vapor streams. Bench-scale and pilot-scale reactors have been studied.

D.6 Adsorption on Carbon or Resin

Adsorption refers to the process by which molecules collect on and adhere to the surface of an adsorbent solid (U.S. EPA, 1988). This adsorption is the result of chemical and/or physical forces. Physical adsorption (the more common type in this application) is the result of Van der Waals' forces, which are common to all matter and result from the motion of electrons. Surface area is a crucial factor in adsorption because adsorption capacity is proportional to surface area. Commercially available adsorbents include activated carbon and synthetic resins.

GAC is the most commonly used vapor-phase treatment method. Activated carbon adsorbents provide a high surface area in a low unit cost material because of the carbon's complex internal pore structure. Commercially available GAC typically has a surface area of 1,000 m^2/gram to 1,400 m^2/gram.

GAC is the most cost-effective organic vapor treatment method for a wide range of applications because of 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. Many vendors sell or lease prefabricated, skid-mounted units that can be put into operation with a few days' notice. Carbon adsorption, however, is economical only for lower mass removal rates. When the vapor concentration is high, carbon replacement or regeneration may be prohibitively expensive.

An alternative to replacing the carbon with offsite disposal or reactivation is onsite regeneration of the carbon. Such systems regenerate the carbon in place, using steam or hot gas to desorb the contaminants. The contaminants recovered in liquid form may then be disposed of or, in some cases, recovered as solvent or used as fuel.

Information on GAC design parameters is available from the carbon vendors. Calgon Carbon Corporation (Pittsburgh, Pennsylvania), Carbtrol Corporation (Westport, Connecticut), Nucon (Columbus, Ohio), and many others supply adsorption isotherms and pressure drop curves for the GAC types they supply. The pressure drop curves are developed as a function of flow rate. Many vendors supply modular, prefabricated GAC units of 200 lb to 2,000 lb of activated carbon that may accommodate flow rates from below 400 scfm to more than 1,000 scfm.

As a rule of thumb, the adsorptive capacity of activated carbon for most hydrocarbons in the vapor stream is about 1 lb hydrocarbon:10 lb activated carbon, and the cost of activated carbon is about $3/lb (all costs included, not just carbon purchase, in 1993 dollars), so the cost of activated carbon treatment can be roughly estimated at $30/lb of hydrocarbon to be treated.

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 have a high tolerance to water vapor. Air streams with relative humidities greater than 90 percent can be processed with little reduction in the adsorption efficiency for organic contaminants. The resin adsorbents are amenable to regeneration on site. Skid-mounted 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. During the desorption cycle, all organic contaminants trapped on the resin are removed, condensed, and transferred to a storage tank. The desorption process used to regenerate the resin is carried out under vacuum, using a minimum volume of nitrogen purge gas. A heat exchanger in the bed heats the resin during regeneration. The same heat exchanger is used to cool the bed to increase sorption capacity while it is on-line treating off-gas (Downey et al., 1994).

D.7 Catalytic Oxidation

Catalytic oxidation is an incineration process that uses catalysts to increase the oxidation rate of organic contaminants, allowing equivalent destruction efficiency at a lower temperature than flame incineration. In catalytic oxidation, the vapor stream is heated and passed through a combustion unit where the gas stream contacts the catalyst. The catalyst accelerates the chemical reaction without undergoing a chemical change itself. The catalyst increases the oxidation reaction rate by adsorbing the contaminant molecules on the catalyst surface. Sorption phenomena on the catalyst serve to increase the local concentration of organic contaminants at the catalyst surface and, for some organic contaminants, reduce the activation energy of the oxidation reaction. Increased concentration and reduced activation energy increase the rate of oxidation of the organics (Kiang, 1988). Figure 2 shows a schematic of a catalytic incinerator unit.

The active catalytic material typically is a precious metal (e.g., palladium, platinum) that provides the surface conditions needed to facilitate the transformation of the contaminant molecules into carbon dioxide and water. The catalyst metal is supported on a lower cost, high surface area metallic or ceramic support medium.

The metal catalyst and support are exposed to the heated off-gas in a catalytic oxidation unit. The catalytic oxidation unit uses either a fixed-bed or a fluidized-bed system. Fixed-bed systems include metallic mesh, wire, or ribbon or ceramic honeycomb supporting the catalyst metal or a packed bed of catalyst-impregnated pellets. Fluidized beds also use catalyst-impregnated ceramic pellets but operate at sufficiently high flow to move and mix the pellets during treatment (U.S. EPA, 1986).

The main advantage of catalytic oxidation versus thermal incineration is the much lower temperature required with a catalyst. These systems typically operate at 600°F to 900°F (CSM Systems, 1989), versus temperatures of 1,400°F or higher for flame incineration. The lower temperature results in lower fuel costs, less severe service conditions for the incinerator materials of construction, and reduced NO_x production. Natural gas or propane is a typical fuel used for supplemental heating when the contaminated vapor streams do not contain sufficient heat value for self-sustaining incineration. Energy costs can be further reduced by reclaiming heat from the exhaust gases (i.e., using the exhaust gas flow to preheat the influent vapor stream).

Careful monitoring of extraction gas concentration and reactor temperature is required to prevent overheating of the catalyst. Overheating can damage the catalyst metal surface and/or the support-reducing catalytic activity. The allowed influent organic vapor concentration depends on the heat value and LEL of the influent vapor stream. Concentrations over 3,000 ppmv VOCs normally are diluted with air to prevent excessive energy release rates and to control the temperature in the catalytic unit. Safety is also a concern with these units, as with any incineration method. The maximum permissible total hydrocarbon concentration varies by site but usually is below 25 percent of the LEL. The total hydrocarbon concentration in the vapor is continuously measured at the inlet to the catalytic unit to control the dilution air flow.

Treating off-gas-containing chlorinated compounds, sulfur-containing compounds, or nitrogen-containing compounds deactivates the catalyst because of the chemical reaction of the catalyst metal with halogens or strong sorption of SO_x and NO_x on the catalyst. Some catalysts are specially designed to treat chlorinated compounds. 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).

The significant cost elements of a catalytic oxidizer are the capital cost (or rental) of the unit, operations and monitoring, maintenance, and makeup fuel cost. A catalytic oxidation unit for treatment of 100-cfm off-gas flow would have a capital cost of approximately $40,000 to $60,000 (in 1991 dollars) (AFCEE, 1992). Operations, maintenance, and monitoring costs are site specific. Makeup fuel is required if the hydrocarbon concentration falls below the level necessary to maintain the required temperature. At the Hill AFB 914 site (Smith et al., 1991),

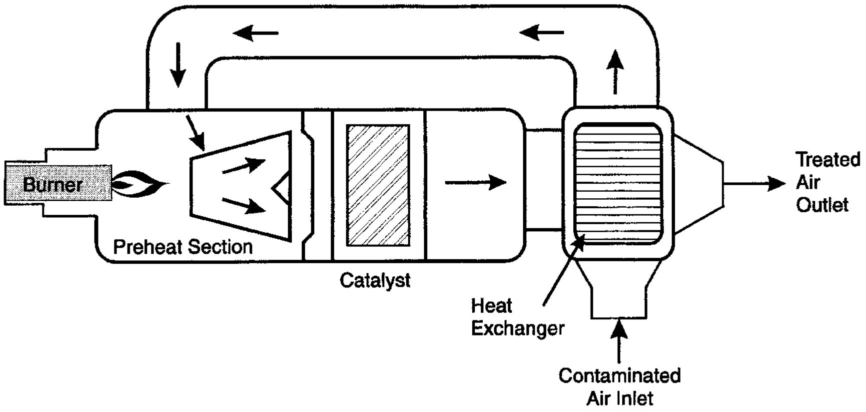

Figure 2. Schematic of catalytic incinerator unit.

the extracted hydrocarbon concentration was approximately 600 ppmv and the flow rate was 1,500 cfm. To maintain the minimum temperature, an average of 1,500 gal of propane was used every month at an average cost of $2,000 per month. All thermal oxidation processes require makeup fuel to treat low-concentration waste streams, and the makeup fuel generally is proportional to the operating temperature. Some fuel may be saved by heat recuperation.

D.8 Flame Incineration

Flame incineration is a process that uses high-temperature direct flame combustion to produce rapid oxidation of organic contaminants. Flame incinerators for treatment of organic vapors in off-gas are typically single-chamber, refractory-lined units containing an open burner. Flame incinerators are often equipped with heat exchangers where hot combustion gases leaving the incinerator are used to preheat the incoming off-gas stream. Heat recovered from the combustion gas improves thermal efficiency and reduces fuel costs. When operated with an adequate temperature and residence time, flame incineration treatment oxidizes 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°F to 1,600°F and a residence time of 1 second (AFCEE, 1992). Makeup fuel is usually necessary to maintain the temperature required to ensure adequate mineralization. Natural gas or propane typically serves as the supplemental fuel. 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 of.

Safety is a major design requirement for flame incinerators and other thermal destruction units. Requirements for safety provisions are derived from National Fire Protection Association (NFPA) standards and applicable state requirements. In most applications, influent concentrations are limited to 25 percent of the LEL (AFCEE, 1992). The LEL for gasoline is between 12,000 ppmv and 15,000 ppm, depending on the gasoline grade (Little, 1987).

Direct incineration is not appropriate for influent vapor streams containing chlorinated compounds. Complete combustion of these compounds generates corrosive hydrochloric acid vapors. Partial or incomplete combustion of chlorinated compounds could result in the production of chlorinated products.

The capital cost of a flame incinerator typically is less than that of a catalytic incinerator. Because of the higher operating temperature, however, fuel use is higher with a flame incinerator. When the flammable contaminant vapor concentration is sufficiently high, the heating value from oxidation of the contaminant reduces fuel use; therefore, at higher hydrocarbon concentrations, flame incineration may be less costly than catalytic incineration. At lower vapor concentrations, the cost of makeup fuel is much greater than for catalytic incineration and the overall cost is probably higher than for catalytic incineration. Flame incineration is generally favored over catalytic oxidation when the combustible organic vapor concentration is higher than about 1,000 ppmv to 5,000 ppmv (AFCEE, 1992).

D.9 Internal Combustion Engines

ICE treatment destroys organic contaminants through oxidation in a conventional engine. ICEs have been used for years to destroy landfill gas. Application of ICEs to destruction of hydrocarbon vapors in air streams is more recent. The first operational unit was installed in 1986.

The ICE used for this technique is an ordinary industrial or automotive engine with its carburetor modified to accept vapors rather than liquid fuel. The air flow capacity of the ICE is determined by the cubic inch displacement of the engine, the engine speed, and the engine vacuum. The capacity (scfm) can be estimated as:

$$\text{Capacity} = \frac{\text{RPM}}{2} \times \frac{\text{CID}}{1{,}728} \times 0.85 \times \left(1 - \frac{\text{EV}}{\text{P}}\right) \quad \text{(Eq. D-1)}$$

where:

RPM = engine speed in revolutions per minute
CID = engine displacement in cubic inches
EV = vacuum at the engine intake in inches of mercury
P = local air pressure in inches of mercury

Therefore, a 140-in.^{3} displacement, four-cylinder engine running at 2,250 rpm and 10 in. Hg engine vacuum with an atmospheric pressure of 30 in. of mercury would have an off-gas treatment capacity of 52 scfm. ICE treatment units are available in sizes from 140 in.^{3} to 460 in.^{3} Currently available ICE treatment units operate the engine near idle conditions. The off-gas capacity could be increased by applying a load to the engine to increase engine speed and decrease engine vacuum. Engine loading by attaching a generator to supply site power has been proposed but is not routinely practiced.

A second required modification to the engines is the addition of a supplemental fuel input valve when the intake hydrocarbon concentration is too low to sustain engine operation. Propane is used almost universally, although one vendor reported that natural gas, when available, can reduce energy cost by 50 percent to 75 percent.

The engines are also equipped with a valve to bleed in ambient air to maintain the required oxygen concentration. Soil vapor may have very low concentrations of oxygen, especially during the initial stages of operation. Ambient air is added to the engine, via an intake valve, at a ratio sufficient to bring the oxygen content up to the stoichiometric requirement for combustion.

A catalytic converter is an integral component of the system, providing an important polishing step to reach the low discharge levels required by many regulatory agencies. A standard automobile catalytic converter, using a platinum-based catalyst, is normally used. Data from the South Coast Air Quality Management District, the air quality regulatory body for Los Angeles and the surrounding area, show that the catalyst reduced concentrations of TPH from 478 ppmv to 89 ppmv and from 1,250 ppm to 39 ppm, resulting in important additional contaminant removal (U.S. EPA, 1991). The South Coast Air Quality Management District requires a catalytic converter to permit this type of system. Catalysts have a finite life span (typically expressed in hours of operation) and must be monitored as that time approaches to ensure that the catalyst is working properly. The length of operation of the catalyst depends on the vapor concentration and whether lead or other potential catalyst poisons are present in the off-gas contaminants. One equipment vendor suggests a range of 750 to 1,500 hours (about 1 to 2 months) of operation. A deactivated catalyst can be replaced easily with any automobile catalytic converter, available at most automobile parts stores.

To date, ICE use appears to be most widespread in California, mostly in the South Coast Air Quality Management District in southern California, which has some of the most stringent air discharge regulations in the country. The South Coast Air Quality Management District has permitted more than 100 ICEs for use in their district. RSI, Inc. (Oxnard, California), has installed more than 30 ICE systems, all in California.

Data obtained from ICE operators and regulators show that ICEs are capable of destruction efficiencies of well over 99 percent (U.S. EPA, 1991). ICEs are especially useful for treating vapor streams with high concentrations of TPH (up to 30-percent volume) to levels below 50 ppm. Tests of BTEX destruction by ICE treatment show that nondetectable levels of contaminants can be achieved in the outlet off-gas in some cases, and outlet concentrations below 1 ppmv can be achieved in many cases. The total destruction capacity may be expressed as mass removal rate. One ICE operator reported a mass removal and destruction rate of over 1 ton per day (about 12 gal/hour).

ICE off-gas treatment units can handle high concentrations of organic contaminants in the extracted air. As discussed above, incineration units (e.g., catalytic oxidation units, flame incinerators) usually are limited to inlet vapor concentrations of 25 percent of the LEL. The inlet concentration for an ICE unit can be in the combustible range, so these units can accept vapor concentrations as high as 40,000 ppmv with no dilution air. As a result, the ICE treatment units have a significant advantage over incineration units when the vapor concentration is higher than 25 percent of the LEL. Inlet vapor concentrations as high as 300,000 ppmv have been reported (U.S. EPA, 1991). The off-gas must still be diluted with air to allow the ICE unit to treat off-gas containing more than about 40,000 ppmv of organics, but only one-quarter as much dilution air flow is needed for the ICE unit compared with an incineration unit.

ICEs also can effectively treat low concentrations (i.e., inlet vapor concentration below 1,000 ppm), although supplemental fuel use increases as the inlet concentration drops below 14,000 ppmv and the cost-effectiveness decreases at reduced intake concentrations. The removal efficiency compares favorably with other treatment methods based on data available from actual system installations.

The use of ICEs as vapor treatment devices for extracted soil vapors offers advantages over conventional treatment methods (carbon, thermal oxidation, or catalytic oxidation), at least for some applications. One advantage of ICEs is the ability to produce power that can provide useful work output. Self-contained units are available that use the ICE to power the blower. The extraction blower consumes only about 25 percent of the useful work produced by the engine. Other uses of the power have included lighting the site, heating a field trailer, or similar ideas. Using the engine as a vacuum source increases the engine vacuum, which has the undesirable effect of reducing air flow capacity (see Equation D-1). As a result, the ICE is usually coupled to a blower to supply the well head vacuum. An added benefit of this system is that vapors cannot be extracted unless treatment also is occurring, eliminating the possibility of vapors bypassing the treatment system.

Another advantage of ICEs is their portability and simple monitoring and maintenance. Typically, the self-contained units are skid-mounted or put on a trailer and can go from site to site very easily. The site requirements may also favor ICEs over other oxidation methods. ICE units are smaller and less noticeable than direct thermal incineration units and may be more appropriate for areas that are intended to remain low profile. Units also have been developed that can be monitored via modem, eliminating costly onsite monitoring.

Noise associated with engine operation could be a concern in areas near residential zones or occupied buildings. Noise can be abated by adjusting engine speed during certain periods, installing a noise suppression fence, or purchasing special low noise ICE models (AFCEE, 1994).

The capital cost of currently available ICE units appears to be somewhat higher but is certainly in the same general range as catalytic incineration and thermal incineration. The costs of ICE treatment units with maximum flow capacities of 65 scfm, 250 scfm, and 500 scfm are $40,450, $73,450, and $98,880, respectively (in 1994 dollars). Propane or natural gas fuel is needed when the inlet vapor concentration is below about 40,000 ppmv. The quantity of added fuel needed increases as the inlet vapor concentration declines. Fuel costs for treating 65 scfm, 250 scfm, and 500 scfm off-gas flow, when all energy is supplied by propane supplemental fuel, are $20/day, $70/day, and $140/day, respectively (AFCEE, 1994). Operations and maintenance costs are site specific. Because ICEs use a much more widely understood technology, gaining regulatory acceptance appears to be easier than for other technologies, and as a result, permitting and monitoring costs should be lower.

D.10 Emerging Vapor Treatment Technologies

This section briefly describes the operating features of several emerging technologies for destruction or concentration of organic contaminants in an off-gas stream. The technologies described are packed-bed thermal treatment, photocatalytic oxidation, and membrane separation.

Packed-bed thermal treatment oxidizes organic contaminants by passing the off-gas stream through a heated bed of ceramic beads. The packed bed increases mixing to promote the oxidation reaction. A vapor stream passes through the packed bed that thermally destroys contaminants. The packing geometry combined with uniform high temperature of the ceramic beads is reported to provide high destruction efficiency for organic vapors in air, without using an open flame. The ceramic beads are heated electrically to bring them to the operating temperature of 1,800°F. No additional energy input is required if the heat value of the vapors is sufficient. This point is near a concentration of 2,000 ppmv. If the concentration is below this value, natural gas or propane can be bled in with influent to maintain the proper temperature. As with any incineration technique, excess air is added to dilute the concentration to safe levels if the influent is too rich. Packed-bed thermal processing has been used to destroy vapor contaminants in the off-gas from several chemical and other industrial plants.

The vendor of the packed-bed technology currently is investigating its applicability to the remediation market (U.S. EPA, 1991). The vendor indicates that this technology has several desirable characteristics for treatment of vapors in off-gas from remediation systems. The removal efficiency is reported to be high and stable over varying operating conditions. Tests have shown efficiencies of 99.99+ percent, and this removal is attained continuously. Another reported advantage is the ability to mineralize chlorinated compounds without the production of chlorinated products of incomplete combustion or degradation of the ceramic beads. Mineral acid vapors would still be produced.

In the photocatalytic oxidation process, VOCs are converted to carbon dioxide and water by exposure to UV light. When chlorinated organics are present, hydrogen chloride gas and/or chlorine are also produced. The off-gas stream enters the photocatalyst unit, where the contaminants are trapped on a catalyst surface. The catalyst surface is continuously exposed to high-intensity UV light. The combination of surface effects from the catalyst and energy input from the UV light allows rapid oxidation of the contaminants. The reported residence time required for 95-percent to 99-percent destruction efficiency is 0.2 seconds (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, therefore, be used as a pretreatment step to increase the efficiency of a second treatment process. The membranes used have dramatically different permeability for air and organic vapor molecules. The difference in permeability allows the organics to concentrate on one side of the membrane and the air on the other side. The concentrated vapor stream can then be further processed to condense and collect the organics or destroy them (U.S. EPA, 1994).

D.11 References

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