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PRINCIPLES AND PRACTICES OF BIOVENTING

VOLUME II: BIOVENTING DESIGN

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ABBREVIATIONS AND ACRONYMS

AFB	Air Force Base
AFCEE	U.S. Air Force Center for Environmental Excellence
AFP	Air Force Plant
AFS	Air Force Station
AL/EQ	Armstrong Laboratory Environics Directorate
ANGB	Air National Guard Base
BTEX	benzene, toluene, ethylbenzene, and xylenes
cfm	cubic ft per minute
DNAPL	dense, nonaqueous-phase liquid
LNAPL	less dense, nonaqueous-phase liquid
NAS	Naval Air Station
NLIN	nonlinear regression procedure
PAHs	polycyclic aromatic hydrocarbons
PCBs	polychlorinated biphenyls
RD&A	Research, Development, and Acquisition
R_I	radius of influence
SAS	Statistical Analysis System
SVE	soil vacuum extraction
TCE	trichloroethylene
TKN	total Kjeldahl nitrogen
TPH	total petroleum hydrocarbon
TVH	total volatile hydrocarbon
UST	underground storage tank
U.S. EPA	U.S. Environmental Protection Agency
VOC	volatile organic carbon

SYMBOLS USED IN CALCULATIONS

C_S	quantity sorbed to the solid matrix
C_V	volumetric concentration in the vapor phase
C_{vsat}	saturated vapor concentration
C_W	volumetric concentration in the aqueous phase
E_a	activation energy
f_{oc}	organic carbon fraction
k	maximum rate of substrate utilization
k_d	endogenous respiration rate
k_o	baseline biodegradation rate
k_B	biodegradation rate
K_d	sorption coefficient
K_{ow}	octanol/water partition coefficient
K_S	Monod half-velocity constant
k_T	temperature-corrected biodegradation rate
MW	molecular weight
P_V	vapor pressure of pure contaminant at temperature T

Q	flowrate
R	gas constant
R_I	radius of influence
S	concentration of the primary substrate (contaminant)
s_x	solubility in water
t	time
T_{abs}	absolute temperature (°K)
χ	mole fraction
X	concentration of microorganisms
Y	cell yield

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VOLUME II: BIOVENTING DESIGN

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

The Armstrong Laboratory Environics Directorate (AL/EQ), an element of the Air Force Human Systems Center, began its research and development program in bioventing in 1988 with a study at Hill Air Force Base (AFB), Utah. Follow-on efforts included field research studies at Tyndall AFB, Florida, Eielson AFB, Alaska, and F.E. Warren AFB, Wyoming, to monitor and optimize process variables. Results from 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 one year. Results from these pilot-scale studies have been culminated to produce this document.

The U.S. EPA's Bioremediation Field Initiative was established to provide the U.S. EPA and state project managers, consulting engineers, and industry with timely information regarding new development in the application of bioremediation at hazardous waste sites. This program has sponsored field research to enable the EPA laboratories to more fully document newly developing bioremediation technologies. As part of the U.S. EPA Bioremediation Field Initiative, the U.S. 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 were used to produce this two-volume manual. Although this design manual is 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. The first volume describes basic principles of bioventing, and this second volume focuses on bioventing design and process monitoring.

1.0 SITE CHARACTERIZATION ACTIVITIES

Site characterization is an important step in determining the feasibility of bioventing and in providing information for a full-scale bioventing design. Chapter 1.0 discusses site characterization methods that are recommended for bioventing sites based on field experience and a statistical analysis of the 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 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 are described in this section as follows:

1. Review existing site data (Section 1.1).
2. Conduct soil gas survey (Section 1.2).
3. Characterize soil (Section 1.3).
4. Perform in situ respiration testing (Section 1.4).
5. Perform soil gas permeability testing (Section 1.5).

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. This review will provide preliminary information for determining whether bioventing is a feasible option for a specific site. Also, the initial data review will help to identify any additional information that will be 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);
- historic water table levels;
- three-dimensional distribution of contaminant;

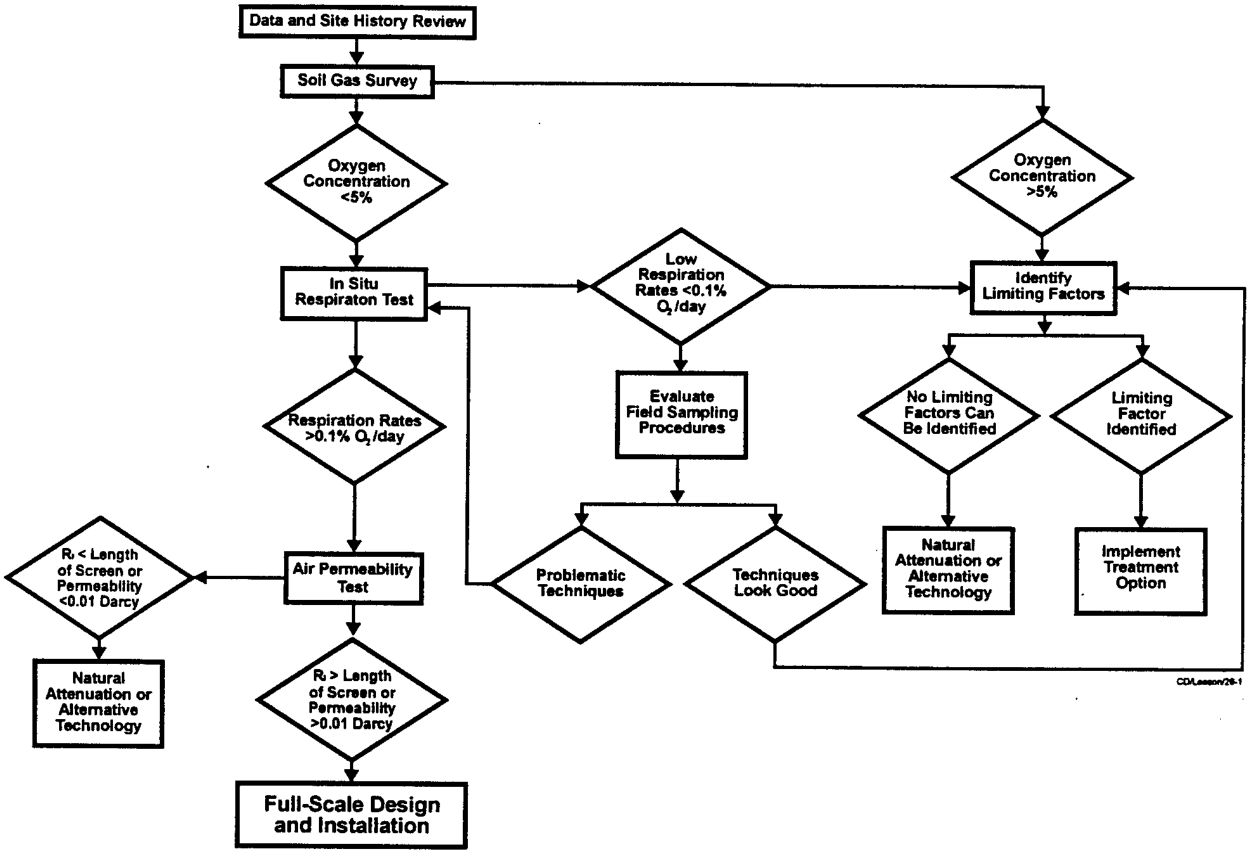

Figure 1-1. Conceptual Decision Tree for Determining the Potential Applicability of Bioventing at a Contaminated Site

- potential for a continuing source due to leaking pipes or tanks;
- particle size distribution or soil gas permeability; and
- surface features such as concrete or asphalt.

At this stage, the most important data 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. At most sites where bioventing is applicable, the contaminant will be 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. The bioslurping technology combines bioventing and free product removal and is currently under development by the Air Force (Kittel et al., 1995).

Data on historical water table levels also are important to determine whether contamination is accessible 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. Developing a three-dimensional distribution of the contaminant will provide information necessary for generating an initial estimate of the screen depths and size of the bioventing system that will be required. This initial estimate will provide guidelines 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 any site. Contaminated sites often are created by leaking underground pipes or tanks. These sources must be eliminated if bioventing is 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 critical parameters. However,

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

unless these values are extreme (e.g., saturated clay), initial treatability studies should be conducted to determine bioventing applicability.

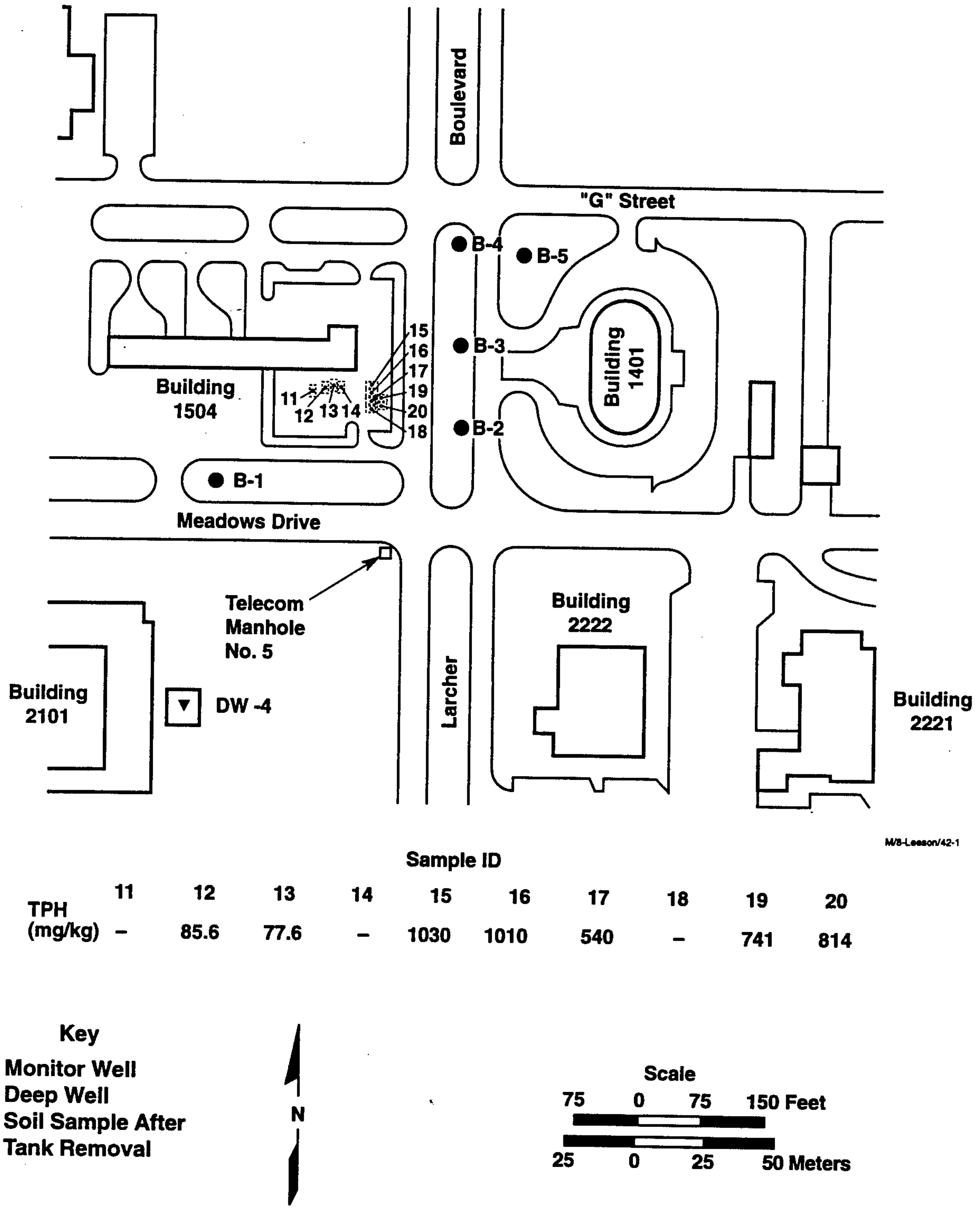
Example 1-1 illustrates review and evaluation of existing site data.

Example 1-1. Review of Existing Data and Site History: We are considering bioventing at Area of Concern (AOC) A at Keesler Air Force Base (AFB) and have the following information:

- The soil was contaminated by leakage from 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, we can conclude the following:

- 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 there are groundwater monitoring wells shown in Figure 1-2, it is likely that some information exists. Therefore, we will attempt to find the additional information but will plan also to collect free product and water level measurements during the soil gas survey phase.
- The quantity of the release is unknown because contamination occurred over a long period of time. However, the limited soil sampling provides a general guideline for the area in which to conduct a soil gas survey.
- Because the storage tanks were removed, a continuing source of contamination is not a factor.
- Particle size distribution is known. Soils are sandy, making this site an excellent candidate for bioventing.



Sample ID	11	12	13	14	15	16	17	18	19	20
TPH (mg/kg)	-	85.6	77.6	-	1030	1010	540	-	741	814

Figure 1-2. Site Map Showing Well Locations and TPH Soil Concentrations at AOC A, Keesler AFB, Mississippi

1.2 Soil Gas Survey

At sites where the contamination is at sufficiently shallow depths (typically <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 that bacteria capable of degrading the contaminants of concern are present, given that soil gas in uncontaminated vadose zone soils generally will exhibit 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 will 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 ambient air as a result of biological and mineral reactions in the soil. Many compounds and elements may be present in soil gas due to 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 that degrade 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%) and soil gas carbon dioxide (a metabolite of hydrocarbon degradation) may be high (typically >10%). 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 often is 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 will continue 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 will be naturally attenuated over time.

Carbon dioxide is produced as a by-product of the complete aerobic biodegradation of hydrocarbons and also can be produced or buffered by the soil carbonate cycle (Ong et al., 1991). Carbon dioxide levels in soil gas generally are elevated in fuel contaminated soils when compared to levels in clean background soils. In many soils, higher carbon dioxide concentrations correlate with low oxygen levels; however, this is not always true. Due to 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).

It is important to compare soil gas survey results for a contaminated area with those obtained from an uncontaminated area. Typically, soil gas concentrations in an uncontaminated area will be significantly different, with oxygen concentrations approximately equal to ambient concentrations and very low carbon dioxide concentrations ($<0.5\%$).

1.2.1.2 Hydrocarbon Vapors

Volatile hydrocarbons found in soil gas can provide valuable information on the extent and magnitude of subsurface contamination. Fuels such as gasoline, that 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 through volatile hydrocarbon monitoring. Methane frequently is 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 that use 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 intended as guidelines. Because of widely varying site conditions, site-specific applications will be required. 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 the pilot test vent well(s) and monitoring points are situated. The soil gas survey is used to determine if bioventing is required based on whether anaerobic soil gas conditions exist, and to provide 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 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 some sites, soil gas measurements can be taken at a number of 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 ⅝- to 1-inch [1.6 to 2.5 cm] outside diameter [OD]) 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[1].

The method of probe installation will be dictated by soil conditions and depth of contamination. Utility clearances from the local utility companies and digging permits (required at military installations) should be obtained prior to probe installation. Temporary probes are installed

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[1] Refer to Appendix B for recommended specifications and manufacturers for soil gas sampling equipment.

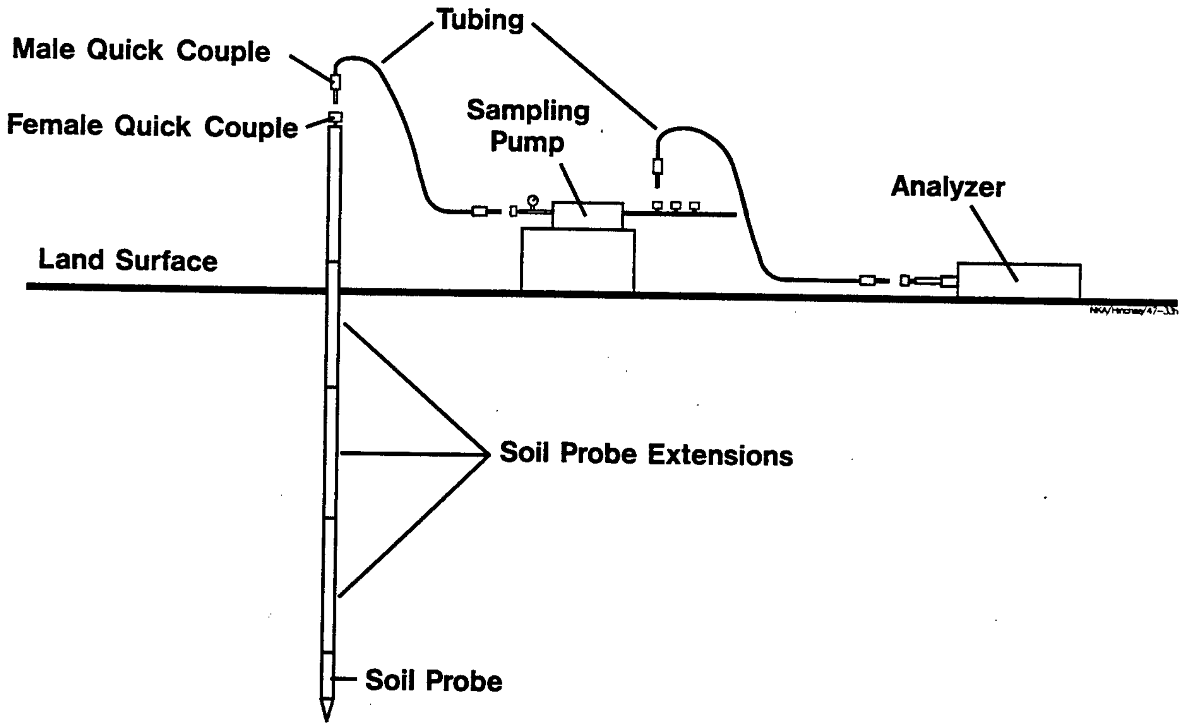

Figure 1-3. Schematic Diagram of a Soil Gas Sampling System Using the Stainless Steel Soil Gas Probe

using either a hand-held electric hammer or a hydraulic ram. The maximum depth for hammer-driven probes is typically 10 to 15 ft (3 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 to drive the probe and also to collect soil samples.

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

Gaseous concentrations of carbon dioxide and oxygen can be analyzed using an O_2/CO_2 analyzer. The analyzer generally will have an internal battery-powered sampling pump and range settings of 0 to 25% for both oxygen and carbon dioxide. Prior to taking measurements, the analyzer should be checked for battery charge level and should be calibrated daily using atmospheric concentrations of oxygen and carbon dioxide (20.9 and 0.05%, respectively) and a gas standard containing 0.0% oxygen, 5.0% carbon dioxide, and 95% 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 that use a platinum catalyst detector system also are 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 measurements are taken 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 the 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. Heavier hydrocarbons will be retained by the carbon trap while methane and other lighter-molecular-weight hydrocarbons pass through to the detector.

Electric motor-driven sampling pumps are used to both 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 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 O_2/CO_2 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 O_2/CO_2 analyzer is connected to a tee in the outlet tubing to monitor O_2/CO_2 concentrations in the extracted soil gas. The magnitude of vacuum measured during purging is inversely proportional to soil permeability and will determine 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 is continued until oxygen and carbon dioxide concentrations stabilize, indicating the purging is complete. Before the pump is turned off, 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 is opened, 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 that would introduce fresh air and dilute the soil gas sample. One method which may be utilized in low-permeability soils is described in the following paragraph.

After the sampling point is purged, a soil gas sample is collected in a Tedlar® bag which is inside an air-tight chamber. The chamber is connected to the sampling point via a hose barb that passes through the chamber wall and 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 with either a valve or the sampler's finger. The partial vacuum created by the pump within the chamber will draw 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. Then the chamber is opened, the Tedlar® bag valve is closed, and the bag is removed from the chamber. The soil gas sample is analyzed by attaching the O_2/CO_2 and TPH analyzers directly to the Tedlar® bag. The advantage of this method is that the sampling pump is no longer in line, thereby shortening the sampling train and minimizing 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 typically is 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, thus allowing the use of less vacuum. Difficulty extracting soil gas from a soil gas probe can be caused also 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 can be the result of either 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.

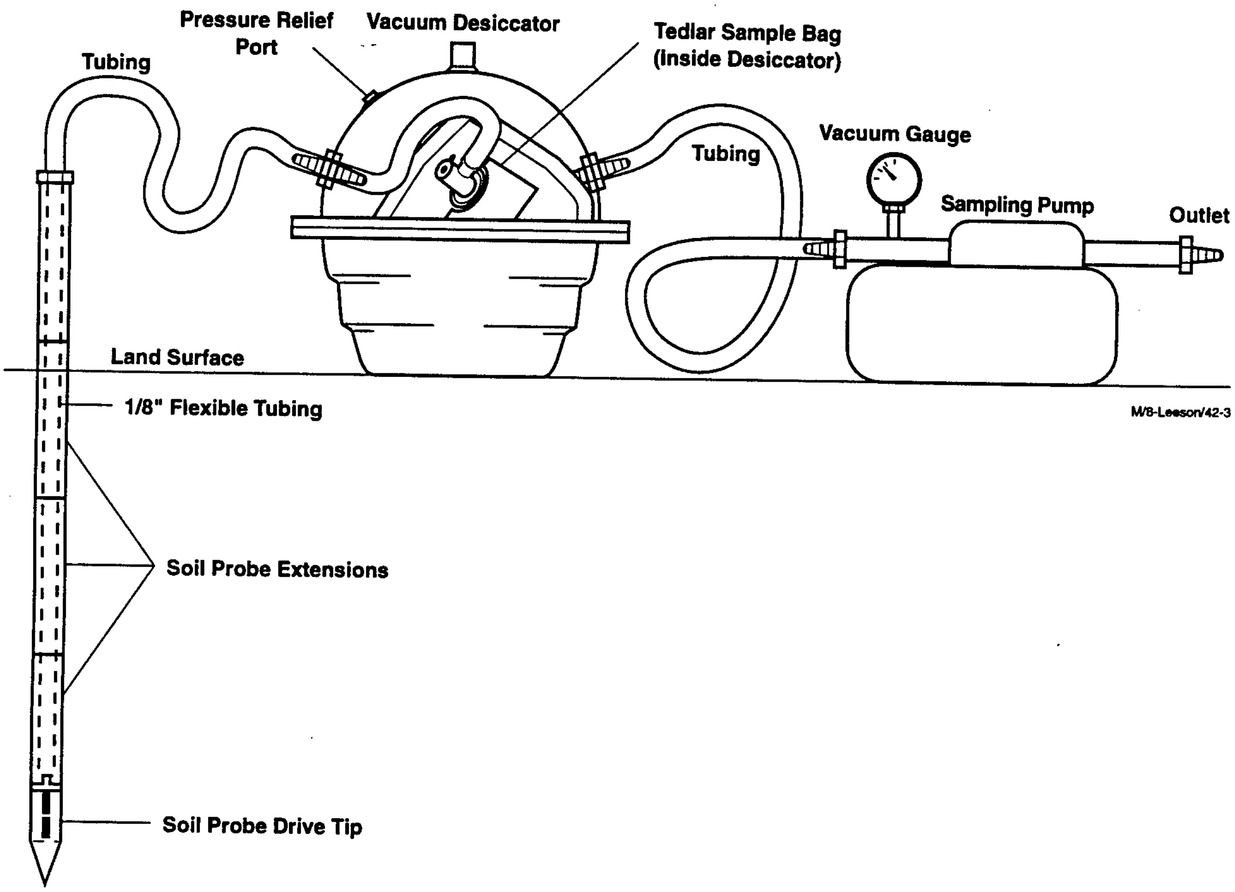

Figure 1-4. Schematic Diagram of a Soil Gas Sampling System for Collection of Soil Gas from Low Permeability Soils

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 work only 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.

Water also can be drawn into the point in unsaturated soils if a vacuum in excess of capillary pressure is created. In this case, the extracted flow typically is a mixture of water and soil gas. Frequently, a water trap can be used before the sampling pump to remove the water and make it possible to collect and analyze a soil gas sample.

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 and that it is appropriate to proceed to in situ respiration testing. If soil gas oxygen concentrations are high (>5 to 10%), but 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 having 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% oxygen).

Diffusion, biometric pumping, or water table fluctuations can enhance air movement into very shallow, permeable soils and provide a natural oxygen supply[1]. 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 is questionable. It is possible that lower levels of contamination (i.e., < 1,000 mg/kg TPH) could be biodegraded by the natural oxygen supply and no active remediation would be necessary. If higher levels of hydrocarbons are present (≥ 1,000 mg/kg), it is unlikely that the natural oxygen supply is adequate to sustain biodegradation; therefore, it is likely that some other factor is limiting biodegradation. In the authors' experience, soil containing both high oxygen and high hydrocarbon concentrations only occur at moisture-limited sites (the most common case) or sites with toxicity problems (TCE in one case and phenolics in another). The authors are aware of only two cases where the lack of oxygen utilization was not explained by these factors. These occurred at a JP-5 jet fuel site on Fallon Naval Air Station (NAS) in Nevada and at a JP-4 spill site at Davis-Monthan AFB in Arizona. The problem sites are not moisture-limited, and to date no clear explanation has arisen (Engineering-Science, 1994; Kittel et al., 1994). A series of examples of soil gas survey results and data interpretations is 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 to be conducted. First, depth to groundwater and free product thickness were measured at all of the groundwater monitoring wells. Groundwater 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 is not a factor at this site.

A limited soil gas survey was conducted at this site since the area of contamination had recently been defined. Soil gas samples were collected at depths ranging from 2 to 6 ft (1.6 to 1.8 m). Because groundwater 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% 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%, carbon dioxide at 0.1%, and TPH at 120 ppm.

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[1] Refer to 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 (SGS) 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

These levels were more representative of ambient air than of the soil gas concentrations measured at other points at the site, indicating there may be significant dilution of this sample. 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 had produced the same initial results, it could be possible that this monitoring point was plugged causing the sampling train to leak and/or that atmospheric air was short circuiting 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 comprised an underground storage tank (UST) that had leaked diesel fuel. The tank was removed, but an unknown quantity of fuel-contaminated soil remained at the site. Site soils were sandy to groundwater, which occurred at 8 to 9 ft (2.4 to 2.7 m).

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

Low levels of TPH indicate that either little diesel-contaminated soil remains at the site or residual fuels are highly weathered. Near atmospheric oxygen levels at all depths indicate that remaining hydrocarbons are being biodegraded with oxygen supplied by natural diffusion. Carbon dioxide was found at levels above the atmospheric concentration of 0.03%, indicating some biological respiration was occurring. Higher carbon dioxide levels and slightly depressed oxygen levels at PT3 and PT4 indicate that remaining fuel is probably located in this area of the site. Natural aeration appears to be providing sufficient oxygen for biodegradation of remaining fuel residuals.

Example 1-4. Soil Gas Survey at the Aquasystem Site, Westover AFB, Massachusetts: This site consisted of USTs which, when removed, revealed soil contamination. An unknown quantity of mixed-fuels contamination remained in the soil. Site soils were predominantly sand, with groundwater 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. However, the 8 to 9% of oxygen available in

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

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

this area is more than sufficient to sustain in situ biodegradation. Carbon dioxide ranged from 2 to 8.5% and generally increased with depth. The available data suggest that significant natural biodegradation is occurring at the site. It is possible that more oxygen-depleted soil exists in the capillary fringe, and that 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 potential risk that soil contamination poses to groundwater.

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, and groundwater 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.

Low levels of TPH indicate that little diesel-contaminated soil remains at the site or that it is highly weathered. Oxygen levels were significantly depleted near PT2 and generally decreased with depth in points near the oil/water separator. Carbon dioxide levels are elevated in areas with low oxygen, indicating that in situ biodegradation is proceeding in the vicinity of the oil/water separator. It is possible that more oxygen-depleted soil exists in the capillary fringe and that 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 groundwater. One additional note: it is possible that if the oil/water separator was connected to a sanitary line, the biological oxygen demand could be the result of leaking sewage. An analysis of soil gas for benzene, toluene, ethylbenzene, and total xylenes (BTEX) could help to determine whether the oxygen demand is indeed fuel related.

1.3 Soil Characterization

Soil characterization is a critical component of the site characterization process. Of primary importance is the concentration and distribution of contaminants. Because there typically are 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 areal extent of contamination. Described in the

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

following sections are techniques for locating and drilling soil borings[1]. The soil analytical protocol is also discussed.

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 a large number of soil samples to be collected 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 is acceptable in more cohesive soils. The final diameter of the borehole is dependent on the diameter selected for the vent wells, but typically should be at least two times greater than the outside diameter of the vent well.

All drilling and sample collection activities should be observed and recorded on a geologic boring log (Figure 1-5). Data to be recorded includes 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.

It is preferable that all boreholes 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.

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[1] Refer to Appendix B for recommended specifications and manufacturers for the soil sampling equipment.

Battelle **Soil Boring Information**

Client: ______________________

Project: ______________________

Size: ______________________

Site Information

Elevation Datum : ______________________

Elevation in feet from Ground Surface (GS): ______________________

Elevation in feet from Top of Casing (TOC): ______________________

Date Started: ______________________

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.

Results of the Bioventing Initiative indicate that four parameters should always be measured: aromatic hydrocarbons (BTEX), total petroleum hydrocarbons (TPH), moisture content, and particle size. Another measurement, total Kjeldahl nitrogen (TKN), was found to be a statistically significant factor in the statistical analyses of Bioventing Initiative data[1]; but there is no evidence to date that addition of nitrogen will enhance site remediation.

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% and irrigation did substantially improve biodegradation rates[2]. Particle size distribution is an important indicator of permeability. High clay content soils may be difficult to biovent due to 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.

TKN is a nutrient required for microbial growth and respiration; therefore, low TKN levels may affect microbial respiration. However, while a statistically significant relationship has been observed between TKN and oxygen utilization rates. the relationship is weak and unlikely to have practical significance. Therefore, it is only recommended to analyze for TKN if all other explanations for poor bioventing performance have been exhausted (i.e., permeability, moisture content).

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[1] Refer to Section 5.0, Volume I for a discussion of the statistical analyses of Bioventing Initiative data.

[2] Refer to Section 3.2.2.2, Volume I for a discussion of this site.

Table 1-5. Soil Analyses[1] 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 brass sleeves[2]; store at 4°C until analyzed.	Analytical laboratory
TPH	Modified GC method SW8015	Handbook method; reference is the California LUFT[3] manual	Collect 100 g of soil in brass sleeves[2]; store at 4°C until analyzed.	Analytical laboratory
Moisture Content	ASTM D-2216	Handbook method	Collect in a 4-oz glass container with Teflon™-lined cap.	Analytical laboratory
Particle Size Analysis	ASTM D422	Handbook method	Collect 250 g soil in a glass or plastic container.	Analytical laboratory
Total Kjeldahl Nitrogen[4]	EPA 351.4	Handbook method	Collect in a 4-oz glass container with Teflon™-lined cap.	Analytical laboratory

[1] Recommended soil analyses is based on experience and analyses of petroleum-contaminated sites. Additional data may be required at sites contaminated with other compounds.

[2] One sample in the brass sleeves provides sufficient volume for analyses of both aromatic hydrocarbons and TPH.

[3] LUFT = State of California *Leaking Underground Fuel Tank Field Manual*, 1988 edition.

[4] Not recommended for an initial analyses, but only if bioventing performance is poor and other factors such as permeability and moisture content do not account for the poor performance.

1.4 In Situ Respiration Testing

The in situ respiration test was developed to provide rapid field measurement of in situ biodegradation rates. This information is needed 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 each of the Bioventing Initiative sites and at numerous other sites throughout the United States. The in situ respiration test described in this document is essentially the same as the described by Hinchee and Ong (1992), with minor modifications.

1.4.1 In Situ Respiration Test Procedures

The in situ respiration test is conducted by placing narrowly screened soil gas monitoring points into the unsaturated zone of contaminated soils and venting these soils for a given period of time with air containing an inert tracer gas (typically helium). The apparatus for the respiration test is illustrated in Figure 1-6[1]. 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. Given the results, it was evident that measurement of background respiration rates was not necessary since there was little significant respiration. Instead, it is recommended that oxygen and carbon dioxide be measured in an uncontaminated location of similar geology, and, if there is significant oxygen depletion, only then should a background in situ respiration test be conducted since there may be significant background respiration.

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

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[1] Refer to Appendix B for recommended specifications and manufacturers for the in situ respiration testing equipment.

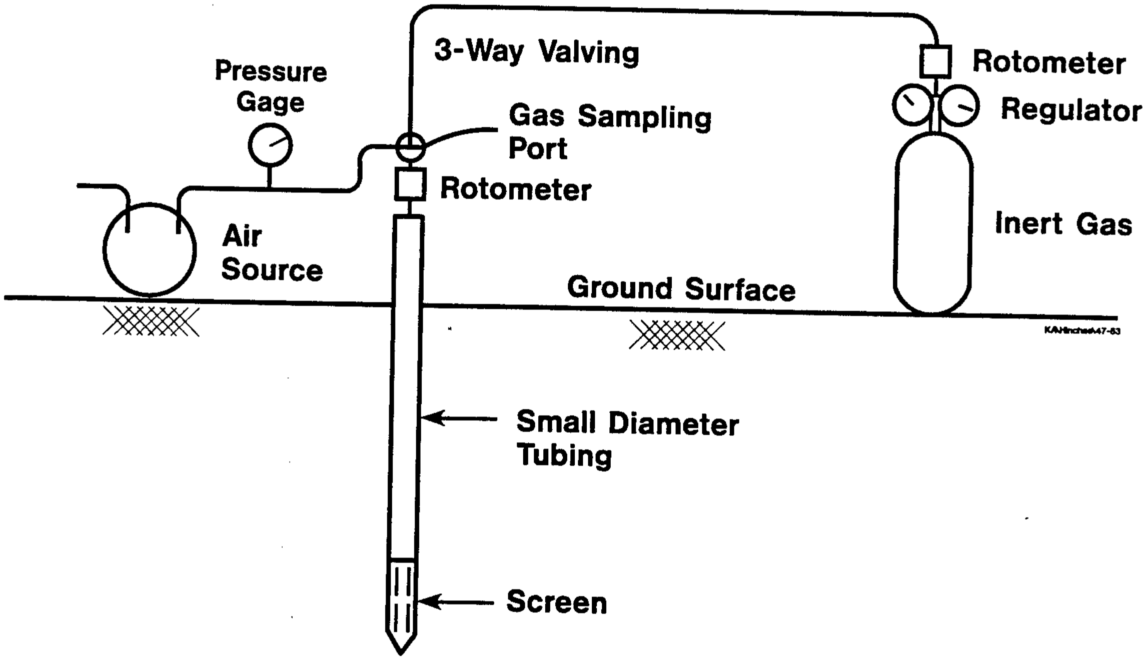

Figure 1-6. In Situ Respiration Test Apparatus

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 prior to air and inert gas injection. A 1 to 3% concentration of inert gas is added to the injection air, which is injected for approximately 24 hours at flowrates ranging from 1.0 to 1.7 cfm (28 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 to 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- to 8-hour intervals. If oxygen uptake is rapid, more frequent monitoring may be required. If it is slower, less frequent readings may be acceptable. The experiment usually is terminated when the soil gas oxygen concentration is approximately 5%.

As discussed in Section 1.2, at shallow monitoring points there is a risk of pulling in atmospheric air in the process of purging and sampling. Excessive purging and sampling may result in erroneous readings. There is no benefit in oversampling 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 to 0.07 cfm (0.85 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 percent oxygen and time. Typically, a rapid linear decrease in oxygen is observed, followed by a lag period once oxygen concentrations drop below approximately 5%. 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 hydrocarbon biodegradation rates 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:

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

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

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

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_{O2} = 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_0 is directly measured in the in situ respiration test. The ratio of hydrocarbons to oxygen required for mineralization, C, can be calculated based on stoichiometry (see Equation (1-1) for hexane) but generally will fall 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

Table 1-6. Oxygen Density Versus Temperature

Temperature (°C)	Temperature(°F)	Density (mg/L)[1]	Density (lb/ft^3)[1]
-33	-27.4	1,627[2]	0.10[2]
-3	26.6	1,446[3]	0.090[3]
0	32	1,429[3]	0.089[3]
5	41	1,403[3]	0.088[3]
10	50	1,378[3]	0.086[3]
15	59	1,354[3]	0.084[3]
20	68	1,331[3]	0.083[3]
27	80.6	1,301[2]	0.082[2]
30	86	1,287[3]	0.080[3]
35	95	1,266[3]	0.079[3]
40	104	1,246[3]	0.078[3]
57	134.6	1,182[2]	0.074[2]
87	188.6	1,083[2]	0.067[2]
127	260.0	975[2]	0.061[2]

[1] Oxygen density at standard pressure.

[2] Density values from Braker and Mossmon, 1980.

[3] Density calculated using the second virial 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 virial 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).

accurately measure due to the difficulty of collecting an undisturbed sample; however, it may be reasonably estimated from the literature. Table 1-7 lists useful literature values for bulk density.

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, but saturated soil is zero. To collect soil gas samples, the gas-filled porosity must be sufficient to allow gas flow. Therefore, it is not possible to conduct an in situ respiration test 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:

$$\theta_a = \theta - \theta_W \tag{1-3}$$

where: θ = total porosity (cm^3/cm^3)

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

The total void volume may be estimated as:

$$\theta = 1 - \frac{\rho_k}{\rho_T} \tag{1-4}$$

where: ρ_k = soil bulk density (g dry soil/cm^3) (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:

$$\theta_W = M \frac{\rho_k}{\rho_T} \tag{1-4}$$

where: M = soil moisture (g moisture/g soil)

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

Soil Description	Porosity	Soil Bulk Density, ρ_k (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

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

Because the water-filled porosity (θ_W) is a difficult parameter to estimate accurately, it frequently is assumed to be 0.2 or 0.3.

Using several assumptions, values for θ_a, ρ_{O2}, 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_{O2}) of 1,330 mg/L
- C, hydrocarbon-to-oxygen ratio of 0.29 from Equation (1-1) for hexane.

The resulting equation is:

$$k_B = \frac{-(k_o)\,(0.25)\,(1{,}330)\,(0.29)\,(0.01)}{1.4} = -\,0.68\ k_o \qquad (1\text{-}5)$$

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. (1991b) were conducting 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%/day are a good indicator that bioventing may be feasible at the site and that it is appropriate to proceed to soil gas permeability testing. If oxygen utilization rates are less than 1.0%/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 of the soil gas survey point locations, because these areas were highly contaminated and were oxygen-limited. Initial soil gas readings were taken at each of the monitoring points and are shown in Table 1-8. Since all locations were oxygen limited, it was decided to inject air at the deepest level of each of the monitoring points (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 % 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.

Example 1-6 illustrates the calculation of oxygen utilization data that is linear with time. However, in some instances, this relationship will not be 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 the Solid Waste Management Unit (SWMU) 66, Keesler AFB. The oxygen utilization rate is determined as the slope 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 hr. As shown, after this point, oxygen concentrations dropped below 5%, and were limiting. The calculated oxygen utilization rate was 11%/day.

The helium data collected at a site will provide insight into whether observed oxygen utilization rates are due to microbial utilization or to 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 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, one should consider any in situ respiration test in which the rate of helium loss is less than the oxygen loss rate to be an acceptable test. If the helium loss rate is greater than the oxygen loss rate, disregard the test from that monitoring point. We do not use the helium loss rate to correct the oxygen utilization rate.

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

Time (hr)	K1-MPA-5.0′			K1-MPA-7.0′		
	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

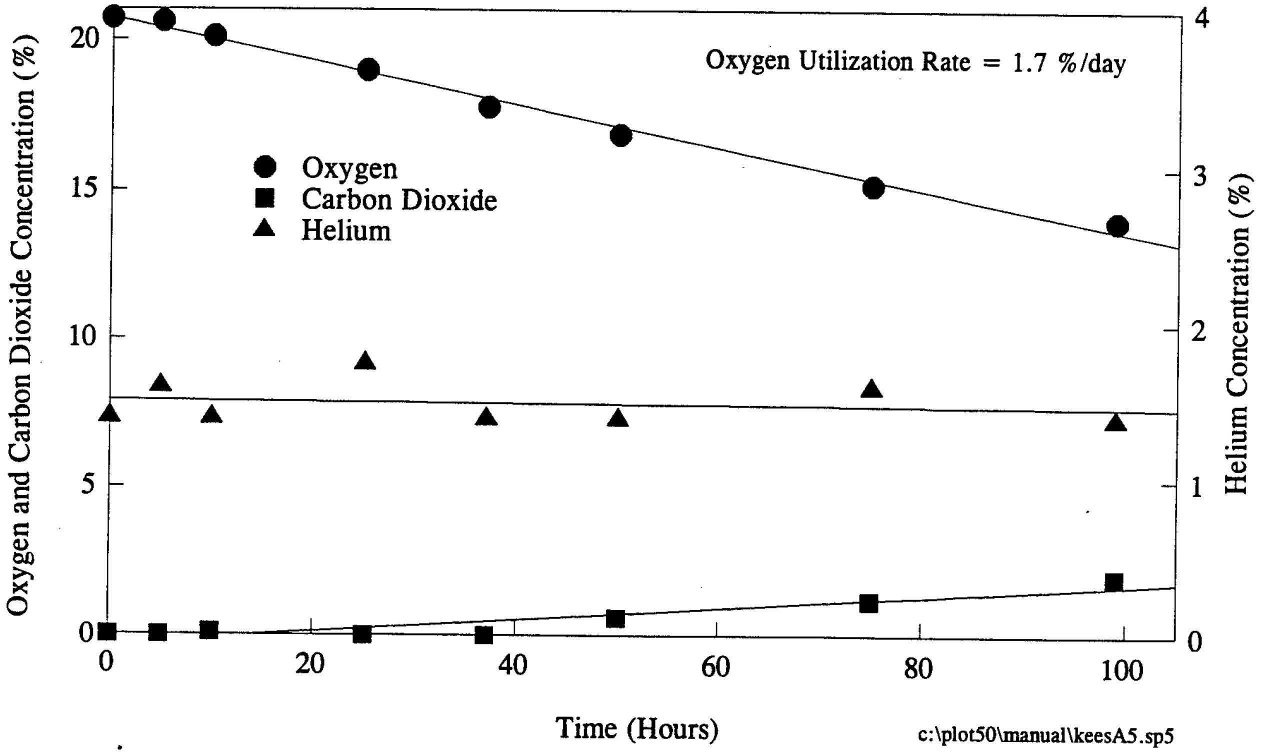

Figure 1-7. In Situ Respiration Test Results with Linear Oxygen Concentration Versus Time at AOC A, Keesler AFB, Mississippi

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

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

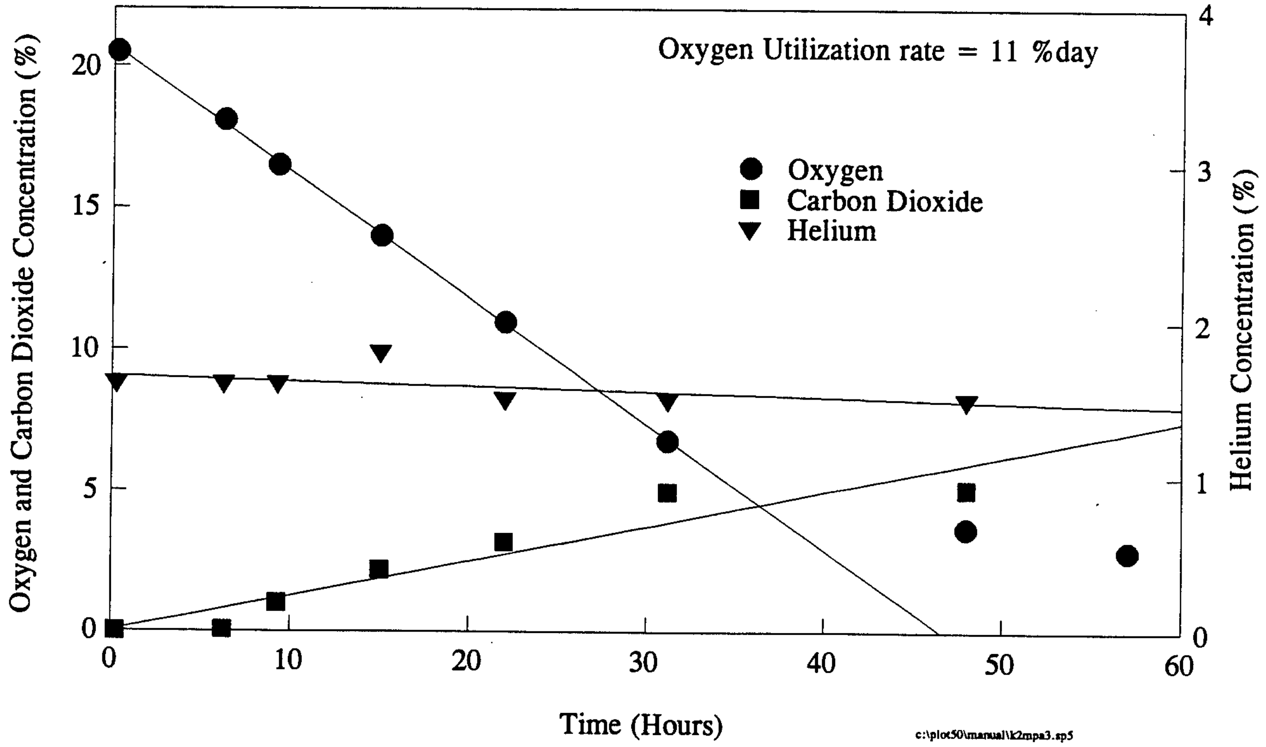

Figure 1-8. In Situ Respiration Test Results with Nonlinear Oxygen Concentration Versus Time at SWMU 66, Keesler AFB, Mississippi

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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 (Figure 1-9) at Tinker AFB started at 1.5% and after 108 hours had dropped to 1.1%, i.e., a fractional loss of ~0.25; and, therefore, an acceptable point. 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 that there was possible short circuiting at this monitoring point. This suggested that the data from this monitoring point were unreliable, and the data were not used in calculating degradation rates.

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 will affect measured biodegradation rates. The factors that may most influence soil gas oxygen and carbon dioxide concentrations are soil pH, soil alkalinity, and iron content. 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 sites studied as part of the Bioventing Initiative, oxygen utilization rates have been higher than carbon dioxide production rates. However, a study conducted at Tyndall AFB site was an exception. That site had low-alkalinity soils and low-pH quartz sands, and carbon dioxide production actually resulted in a slightly higher estimate of biodegradation (Miller, 1990).

In the case of 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., 1991a; Leeson et al., 1995). This is possibly due to the formation of carbonates from the gaseous evolution of carbon dioxide produced by biodegradation at these sites. A similar phenomenon was encountered by van Eyk and Vreeken (1988) 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. However, in data collected from the Bioventing Initiative study, iron concentrations have varied greatly, ranging 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, the Marine Base at Kaneohe, Hawaii, where soil iron concentrations are in the 100,000 mg/kg range.

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

If oxygen utilization rates were determined during periods of low activity, it will be 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[1]. The activation energy, E_a must either be known for the site or calculated by using E_a found at another site, recognizing that 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%/day (0.031%/hr). 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):

$$\frac{dk}{dT} = \frac{E_a}{RT^2} \tag{9}$$

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

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[1] Refer to Volume I for a discussion of the effect of temperature on microbial activity.

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

where: k_T = temperature-corrected oxygen utilization rate (% O_2/day)
k_o = baseline reaction rate = 0.75%/day
E_a = activation energy[1] = 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

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

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

As can be seen from this calculation, the site would require approximately 5 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 flowrate to satisfy oxygen demand at a given site[2]. However, it is necessary also to determine the distance air can physically be moved. 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. On-site testing provides the most accurate estimate of the soil gas permeability. On-site testing also can be used to determine the radius of influence that can be achieved for a given well configuration and flowrate. These data are used in full-scale system design, 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.

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[1] Calculated from a different field site. Refer to Example 3-2, Volume I for a description of the calculation of the activation energy.

[2] Refer to Section 2.2 for a presentation of the calculation of required air flowrates.

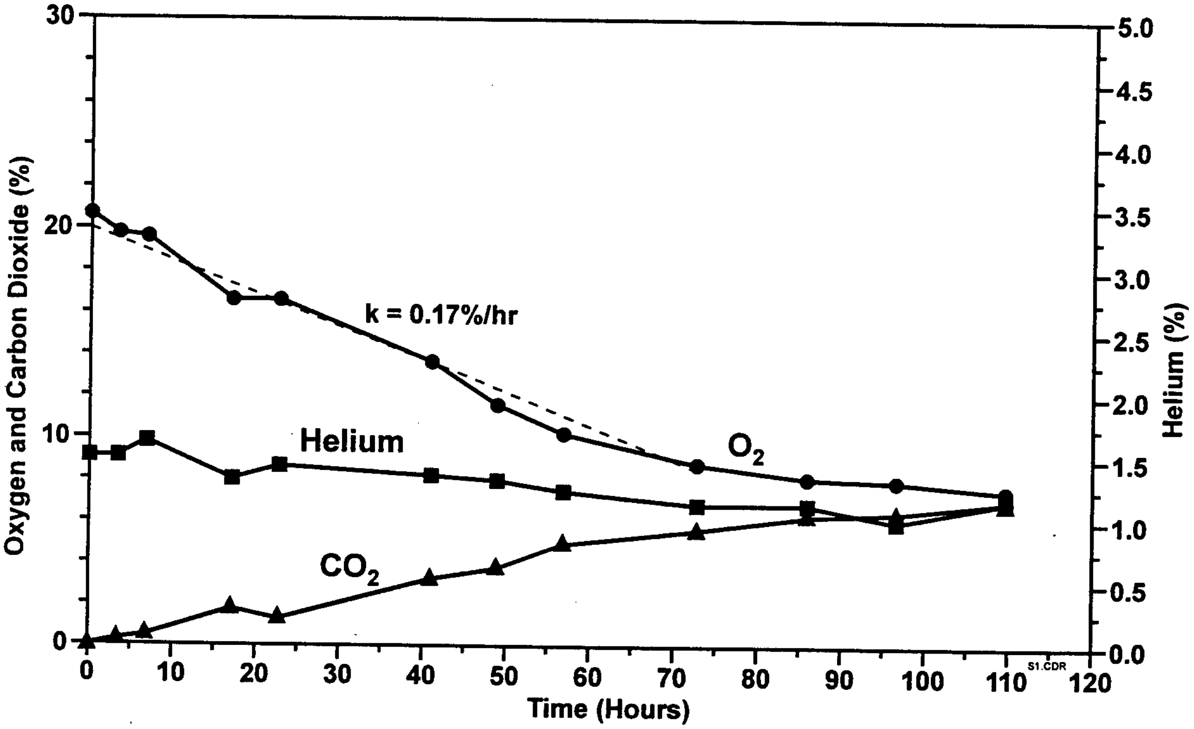

Figure 1-9. In Situ Respiration Test Results With Acceptable Data Based on the Helium Concentration for Monitoring Point S1, Tinker AFB, Oklahoma

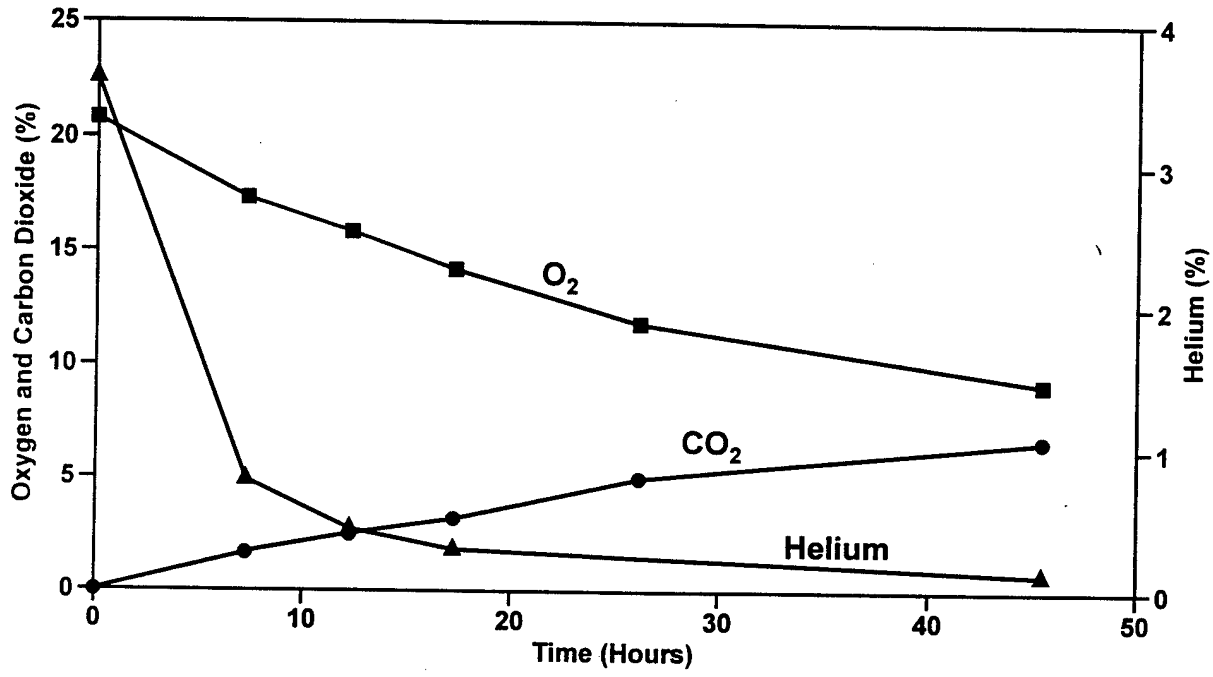

Figure 1-10. In Situ Respiration Test Results With Unacceptable Data Based on the Helium Concentration for Monitoring Point K3, Kenai, Alaska

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 at one 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 will contain a mixture of grain sizes, which generally will increase 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

Several field methods have been developed for determining soil gas permeability (Sellers and Fan, 1991). The most commonly applied 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[1].

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). The HyperVentilate™ computer program was produced by

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[1] Refer to Appendix B for recommended specifications and manufacturers for the soil gas permeability testing equipment.

Johnson for use in storing field data and computing 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 to calculate 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 as the maximum distance from the air extraction or injection well where a sufficient supply of oxygen for microbial respiration can be delivered. We will call the radius of influence measured by increased oxygen the "oxygen radius of influence". In practice, we frequently estimate this radius by measuring a pressure radius of influence. A description of how that is done will follow.

The oxygen and pressure radii of influence are a function of soil properties, but also are dependent on the configuration of the venting well and extraction or injection flowrates, and are altered by soil stratification. The oxygen radius of influence also depends on microbial oxygen utilization rates. At 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[1], the pavement will not significantly impact soil gas flow.

At a bioventing site, the oxygen radius of influence is the true radius of influence; however, for design purposes, we frequently use the pressure radius of influence. The pressure radius of influence is the maximum distance from a vent well where vacuum (in extraction mode) or pressure (in injection mode) can be measured. In practice, we usually use 0.1 inches of water as the cut off pressure. In highly permeable soils, 0.01 inches of water is a better cut off, if it can be reliably

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[1] It is the authors' experience that at most sites, this seal does not occur.

measured. There is a connection between the pressure radius of influence and the oxygen radius of influence; however, there are many variables which are not fully understood. In practice, it has been our experience that when our design procedures are followed, that the oxygen radius of influence is larger than the measured pressure radius of influence, making the pressure radius of influence a reasonably conservative, rapid method for estimating the true radius of influence. The oxygen radius of influence may be determined directly by measuring the distance from the vent well at which a change in oxygen concentration can be detected. However, it may take several days to weeks for equilibrium to be reached and an accurate oxygen radius of influence to be measured. In addition, oxygen utilization rates may change, increasing or reducing the oxygen radius of influence. Therefore, if possible, it is best 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 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 flowrates, with a 1- to 2-hour test per flowrate during the permeability test. Determining the radius of influence at different flowrates will allow for more accurate blower sizing[1]. Recommended flowrates for the permeability test are 0.5, 1.5, and 3 cfm (14, 42, 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.

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).

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[1] Refer to Section 2.4 for a discussion of blower sizing.

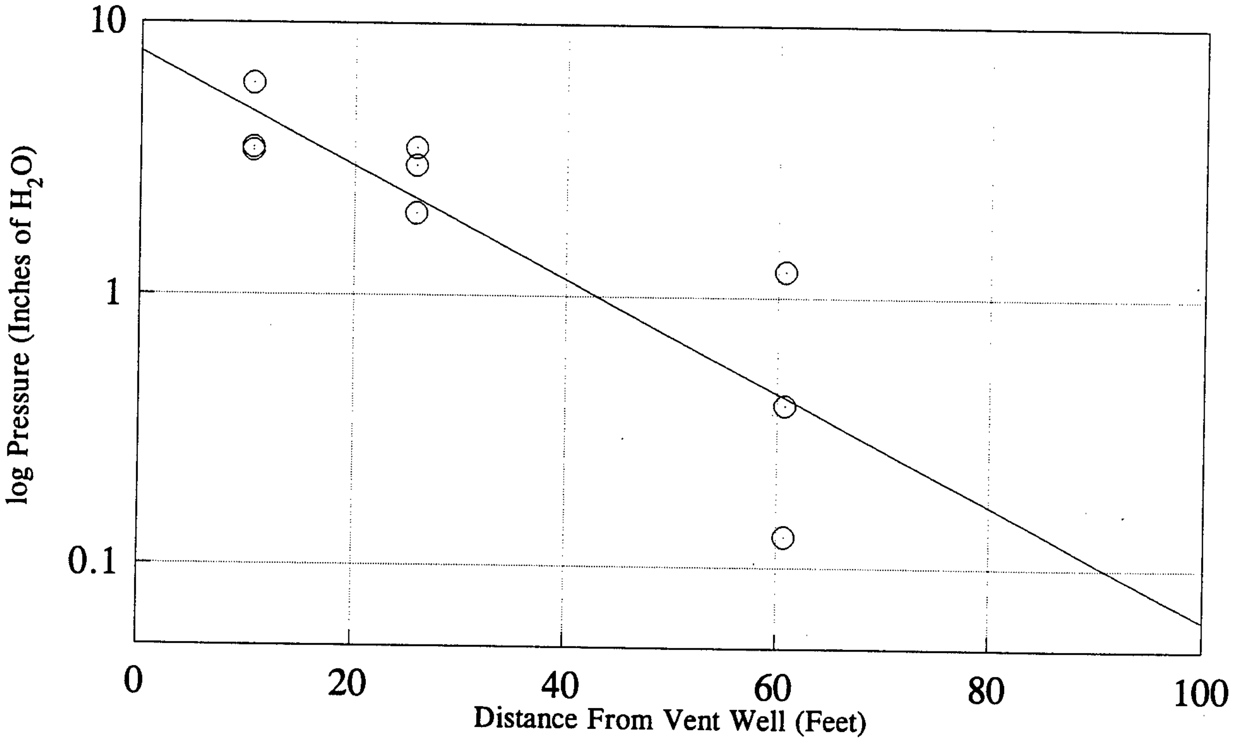

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Figure 1-11. Determination of Radius of Influence at the Saddle Tank Farm, Galena AFS, Alaska

When using pressure radius of influence, it should be remembered that 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 time frame (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 flowrate 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 (>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 it is appropriate to proceed to soil sampling and full-scale design. If either the soil gas permeability or the radius of influence is low (<0.01 darcy or a R_I less than the screened interval of the vent well), bioventing may not be feasible. In this situation, it is necessary to evaluate the cost effectiveness of bioventing over other alternative technologies for site remediation. The cost of installing a bioventing system at a low-permeability site will be driven primarily by the need to install more vent wells, use a blower with a higher delivery pressure, or install horizontal wells.

2.0 SYSTEM DESIGN

The design of a bioventing system is based on 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 (a.k.a. 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 flowrates and often does not involve air extraction.

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

1. Determine required air flow system (injection, extraction, or both [Section 2.1]);
2. Determine required air flowrates (Section 2.2).
3. Determine the working radius of influence.
4. Determine well spacing (Section 2.3).
5. Provide detailed design of blower, vent wells, and piping (Section 2.4).
6. Determine vent well requirements (Section 2.5).
7. 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 will result in minimal discharge of volatile organics to the atmosphere and is less expensive to operate and maintain than air extraction systems.

Under some circumstances, 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 will reduce the risk of moving gases into these areas. This precaution will prevent 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 to 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, despite relatively low in situ respiration rates at monitoring points located far from the injection well (220 ft [67 m]), 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 approximately one-third the rate observed in contaminated soils. Kampbell (1993) found that 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 flowrates low enough to avoid surface emissions. As 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; Reisinger, 1994).

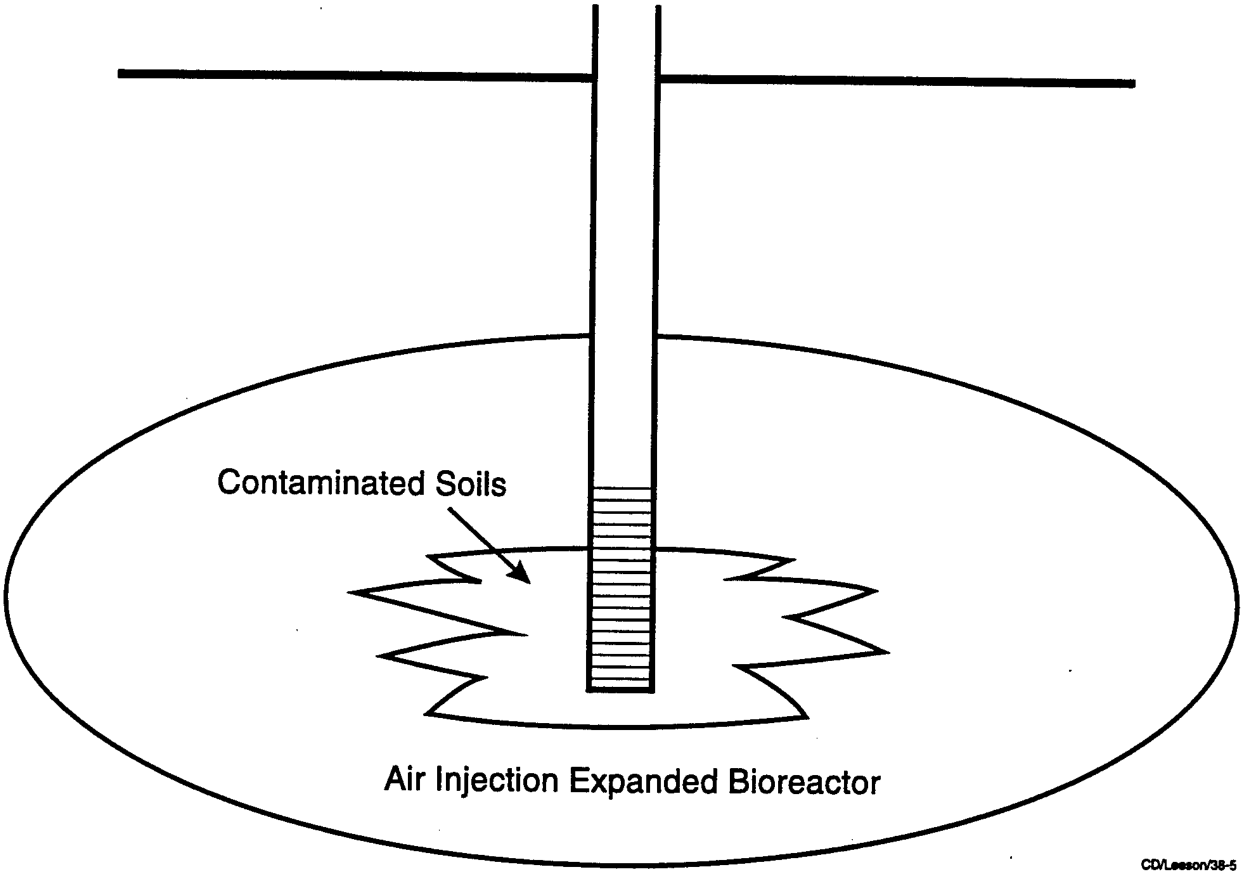

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Figure 2-1. Expanded Bioreactor Created During Air Injection

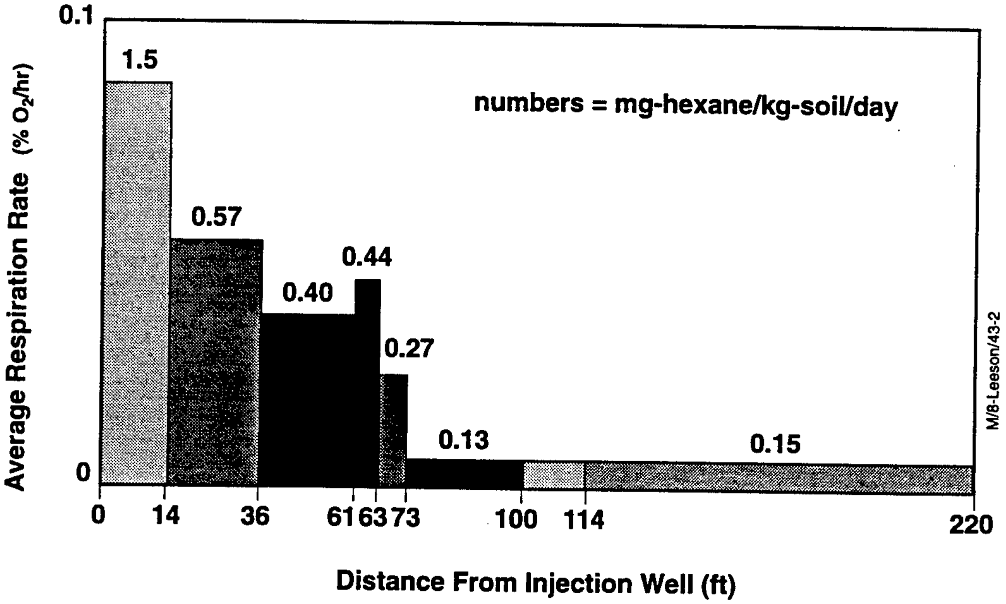


Figure 2-2. Oxygen Utilization Rates, Averaged Over Depth, Versus Distance from the Injection Well at Site 280, Hill AFB, Utah

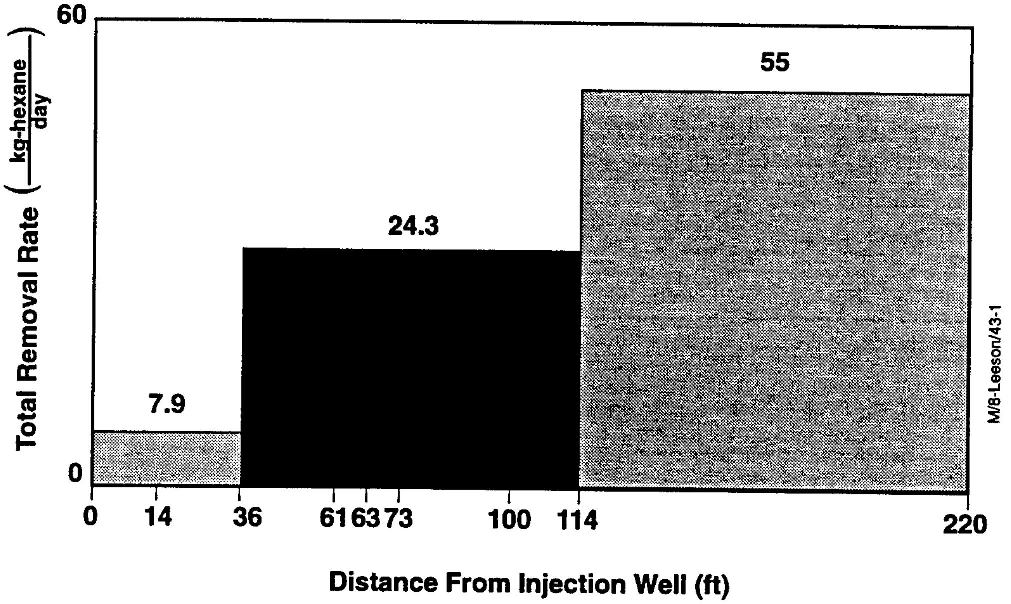
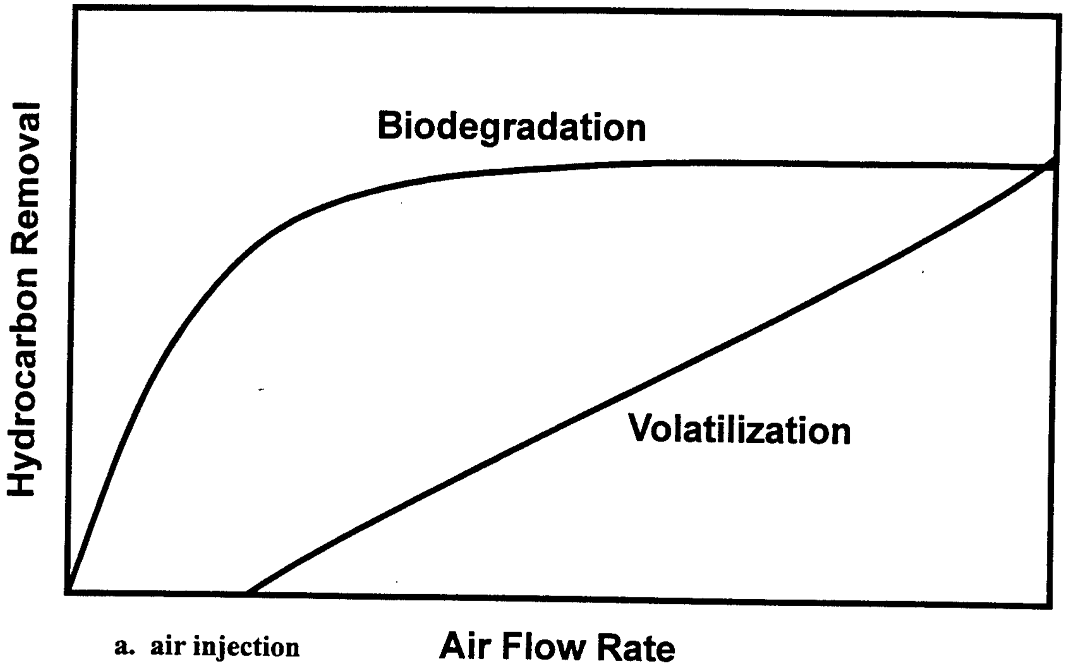
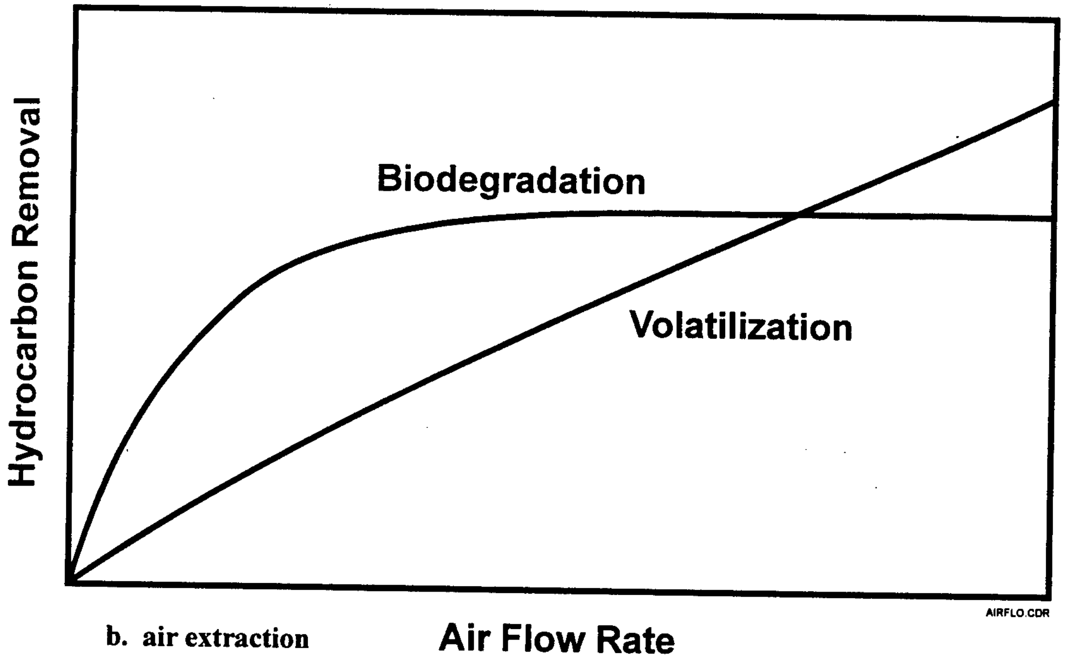


Figure 2-3. Mass of TPH Degraded Versus Distance from the Injection Well at Site 280, Hill AFB, Utah



a. air injection



b. air extraction

Figure 2-4. Hydrocarbon Volatilization and Biodegradation Rates as a Function of Air Flowrate

In addition to creating an expanded bioreactor, air injection has the potential to 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 the capillary fringe will be more effectively treated by lowering the water table. In addition, this dewatering effect frequently results in an increased radius of influence and greater soil gas permeability.

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. If properly designed and operated, an injection system will not result in 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 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 volume because vapors do not move outward to create an expanded bioreactor. The result is less biodegradation and more volatilization. In general, increasing extraction rates will increase both volatilization and biodegradation rates until the site becomes aerated, above which the rate of biodegradation no longer increases. Volatilization generally will continue to increase with increasing extraction rates until the contaminated soil system becomes diffusion-limited. The optimal air flowrate for both injection and extraction is the minimum required to satisfy the 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

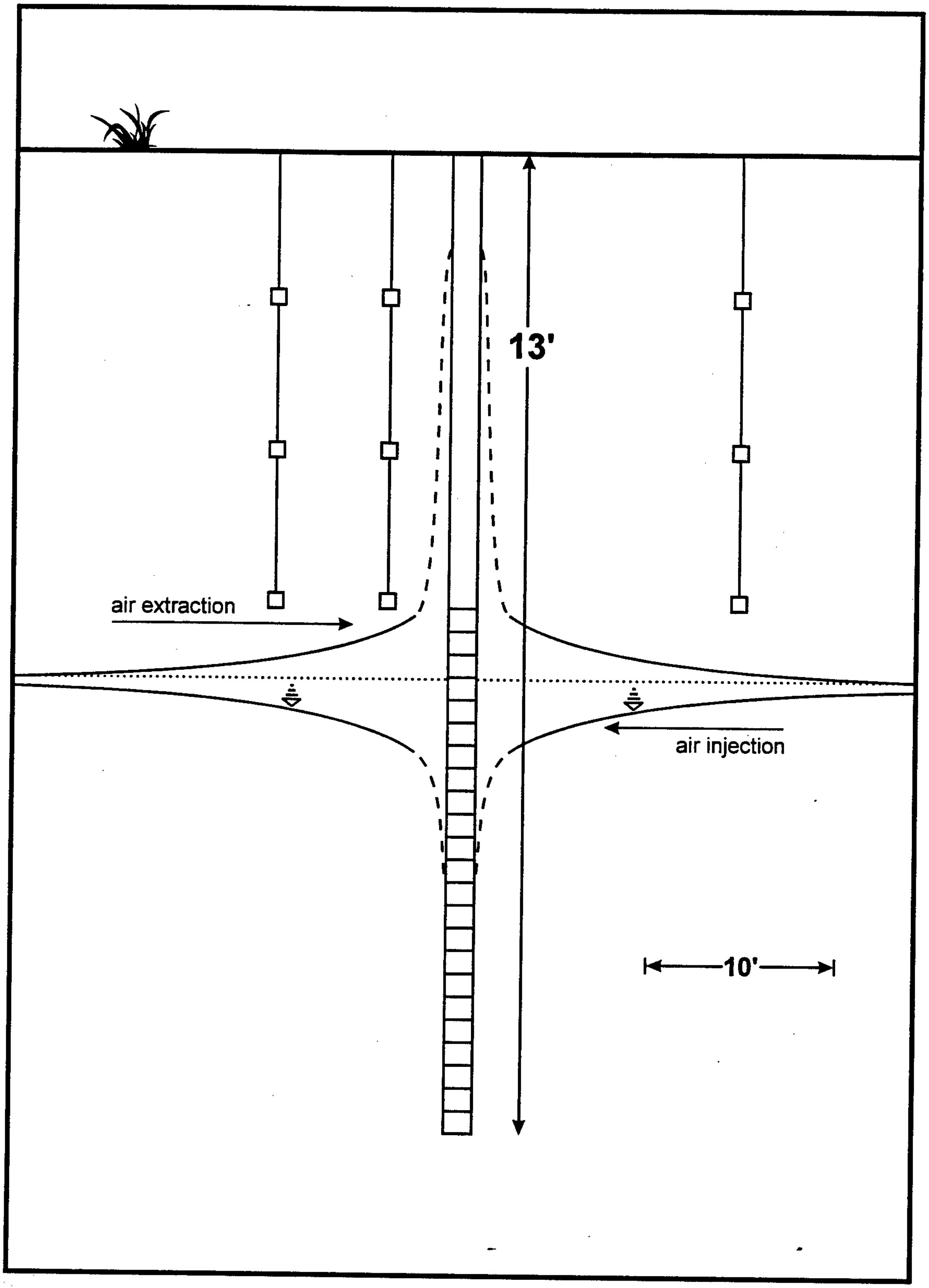


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Figure 2-5. Water Table Depression During Air Injection and Air Extraction

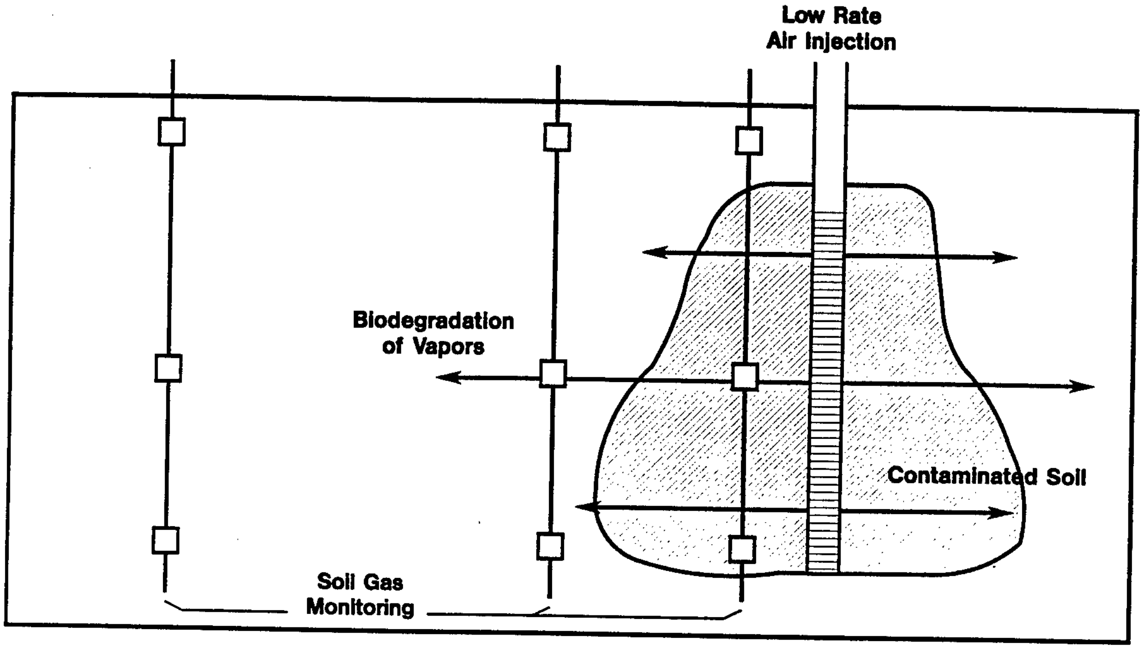

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Figure 2-6. Air Injection Configuration for a Bioventing System site at Tyndall AFB, Miller et al. (1991) found that at the optimal air injection level it was possible to achieve approximately 85% of removal due to biodegradation at the optimal flowrate.

Air extraction creates a partial vacuum in the soil, resulting in a water table and capillary fringe rise or upwelling. This phenomenon has been illustrated in the soil venting literature (Johnson et al., 1990). Because the bulk of contamination often lies 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 will increase soil moisture in the capillary fringe and thus reduce 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 on 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 (1.8-m) 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 rise illustrated in Figure 2-5.

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

Depth (ft)	Permeability (darcy)		Air Radius of Influence (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 explosion-proof blower with explosion-proof wiring normally is required. Extracted soil gas

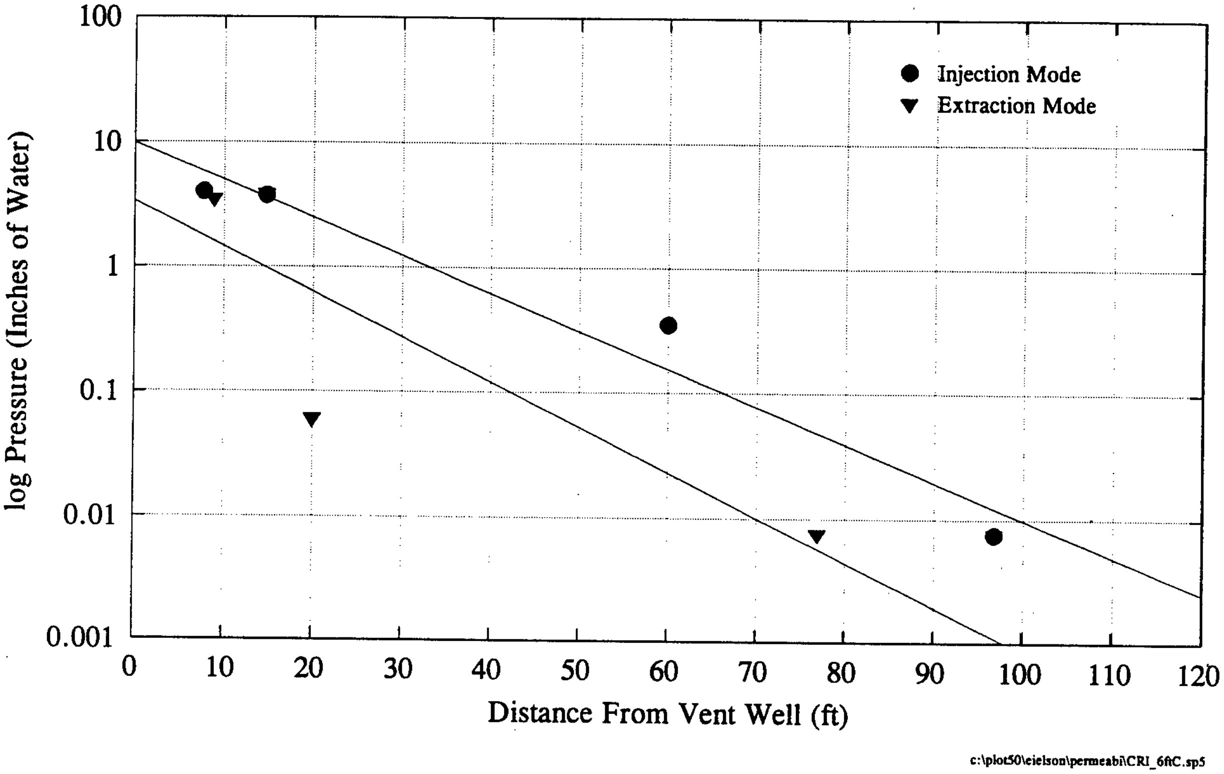

Figure 2-7. **Radii of Influence During Air Injection and Extraction in the Control Test Plot at a Depth of 6 ft at Site 20, Eielson AFB, Alaska**

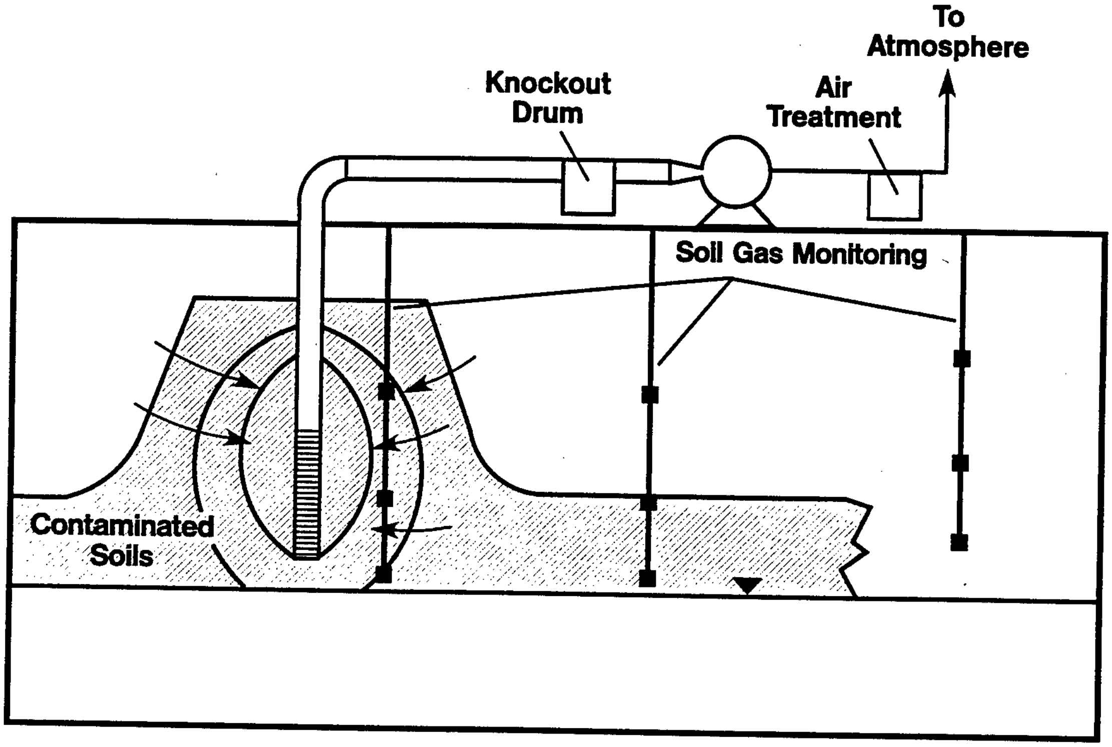

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Figure 2-8. Schematic Diagram of a Basic Air Extraction System typically contains moisture at or near saturation, and a knockout (air/water separator) usually is required to collect condensate, which must be treated or disposed of. Also, in winter 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 will result in point source emissions that may require permitting and treatment. Air treatment will increase remediation costs significantly. Appendix D contains information on options for off-gas treatment.

Currently, air extraction has been selected as the method for oxygenation for only 6 out of the 125 Bioventing Initiative sites. Two of the sites (Capehart Service Station at McClellan AFB and BX Service Station, Patrick AFB) operated in extraction mode for 60 to 120 days, at which time the system was reconfigured for air injection because vapor concentrations had been significantly reduced. 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 were reduced 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 then was recirculated through the soil by injecting air via biofilter trenches located along the perimeter of the site. Phase II was initiated once TVH concentrations were reduced to $<1{,}000$ 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

The decision to use injection versus extraction usually is driven by safety considerations. Air injection should not be used unless a system can be designed that will not push hazardous vapors into structures. Table 2-2 summarizes some of the considerations which will impact the decision.

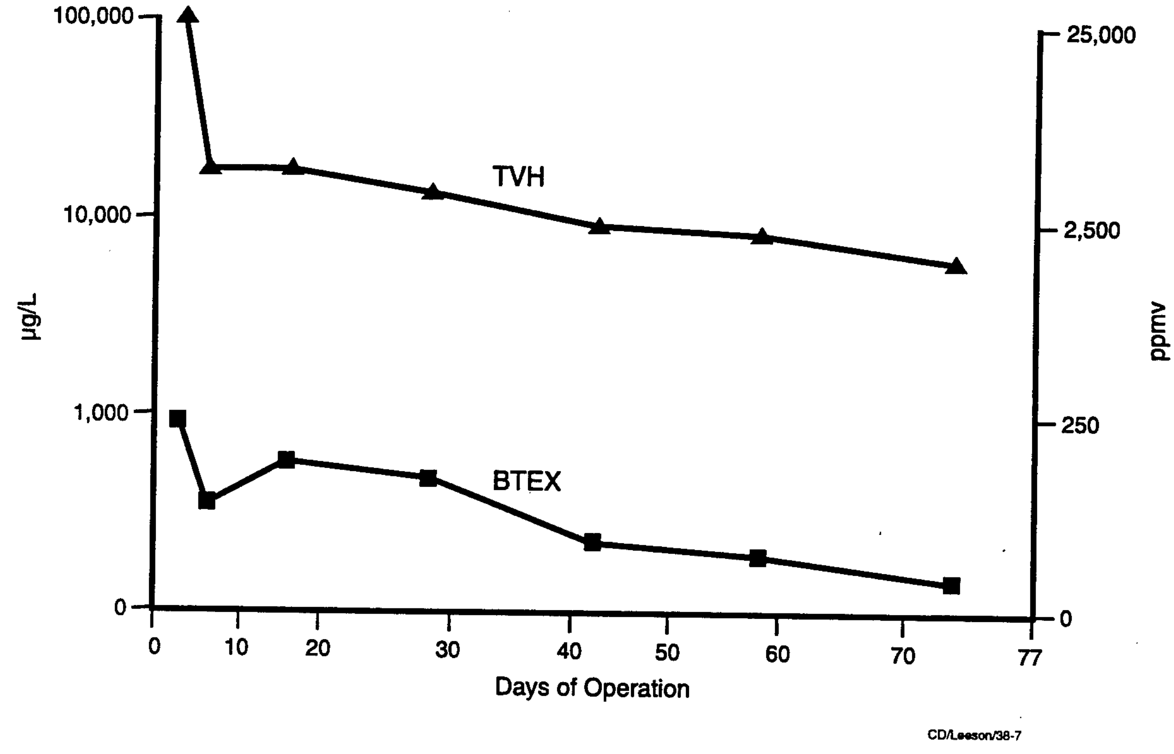

Figure 2-9. Extracted BTEX and TPH Soil Gas Concentrations at Patrick AFB, Florida

Table 2-2. Air Injection Versus Extraction Considerations

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

Numerous options are available that may allow air injection at sites with structures at risk or with property boundaries nearby (Downey, 1995). These options include monitoring the atmosphere in the structure to verify that no contaminant has entered, 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 diagram of such a system is shown in Figure 2-11.

At AOC A at Keesler AFB, Mississippi, a subslab depressurization system is currently in operation as part of the Bioventing Initiative. A schematic diagram 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.

At Site 48 at Eielson AFB, Alaska, a utilidor that is actively used runs through the site. The potential for migration of vapors into the utilidor was high. To eliminate vapor migration into this structure, a horizontal perforated pipe was installed next to the utilidor. A vertical extraction well

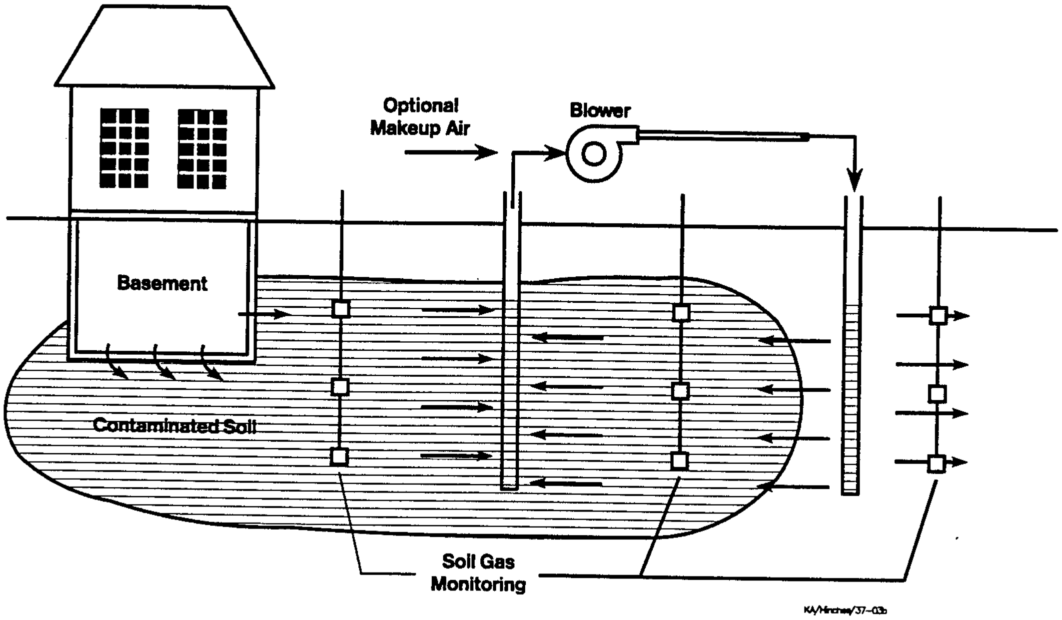

Figure 2-10. Schematic Diagram of an Air Injection System with Reinjection of Extracted Soil Gas

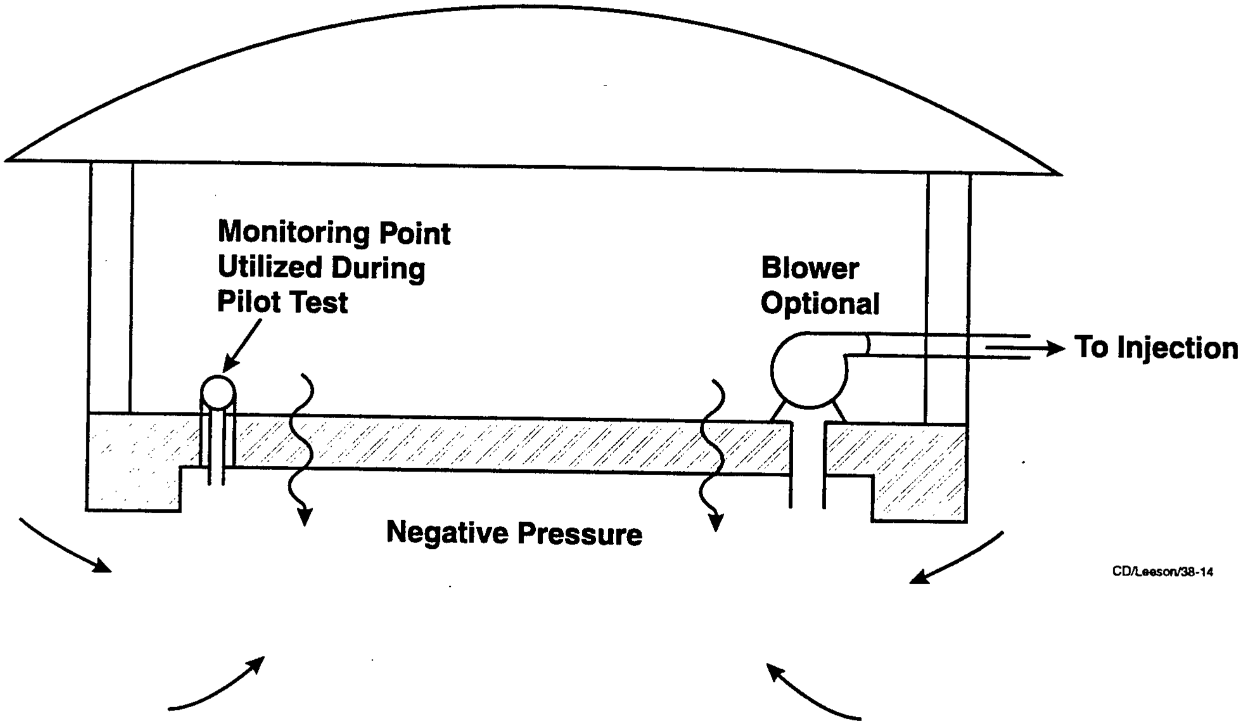

Figure 2-11. Schematic Diagram of Subslab Depressurization

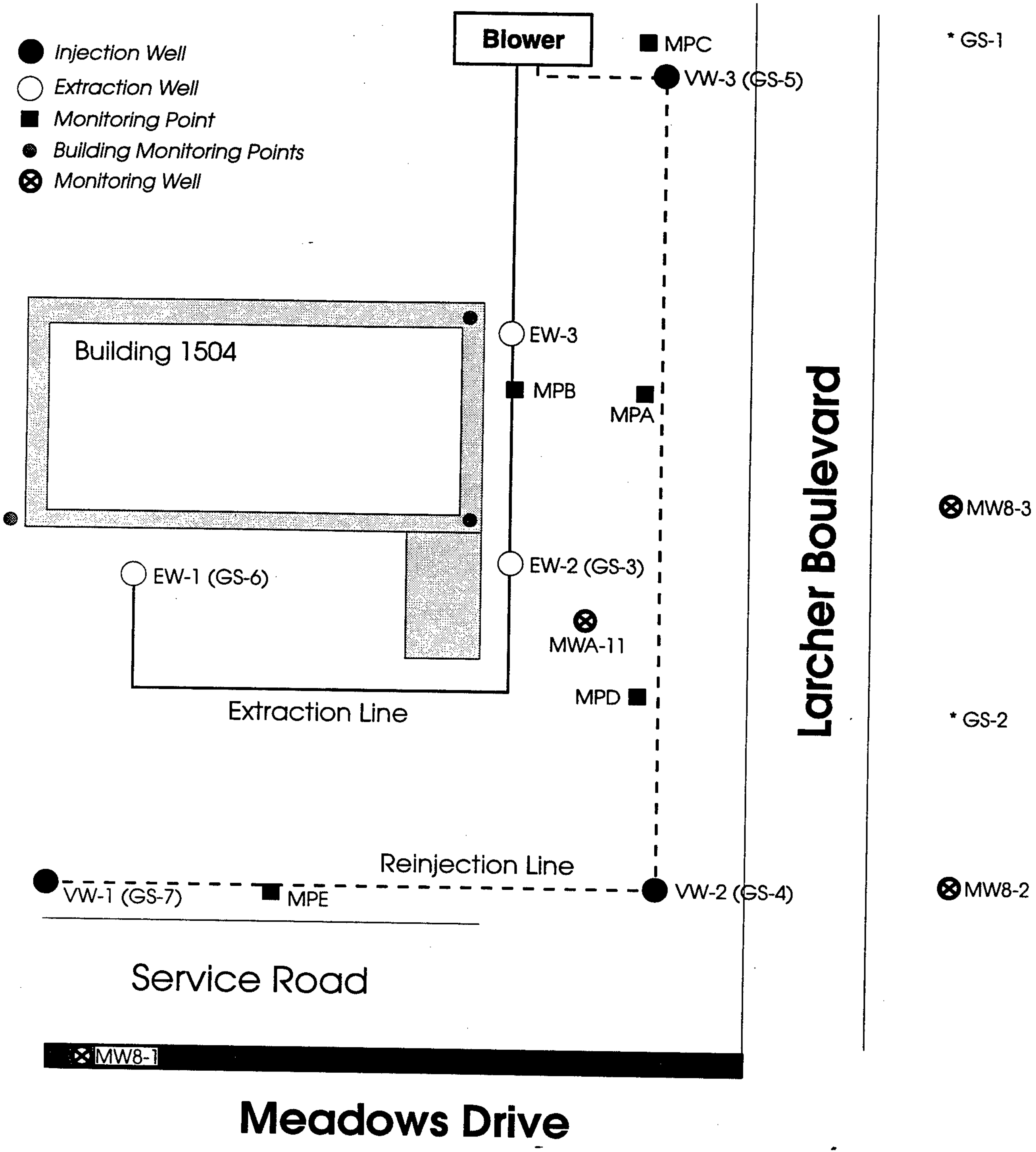

Figure 2-12. Schematic Diagram of the Extraction with Reinjection System at AOC A, Keesler AFB, Mississippi

was connected to the horizontal pipe to extract gas from along the utilidor for vapor control. The extracted soil gas then was reinjected into a contaminated area at the site (Figure 2-13).

2.2 Determining Required Air Flowrates

The flowrate 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 flowrate:

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

where: Q = flowrate (ft^3/min)

k_o = 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 Flowrate: 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[1], and an oxygen utilization rate of 0.25%/hr, the flowrate is calculated as follows:

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

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

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[1] Refer to Section 1.4.2 on using moisture content to estimate this parameter.

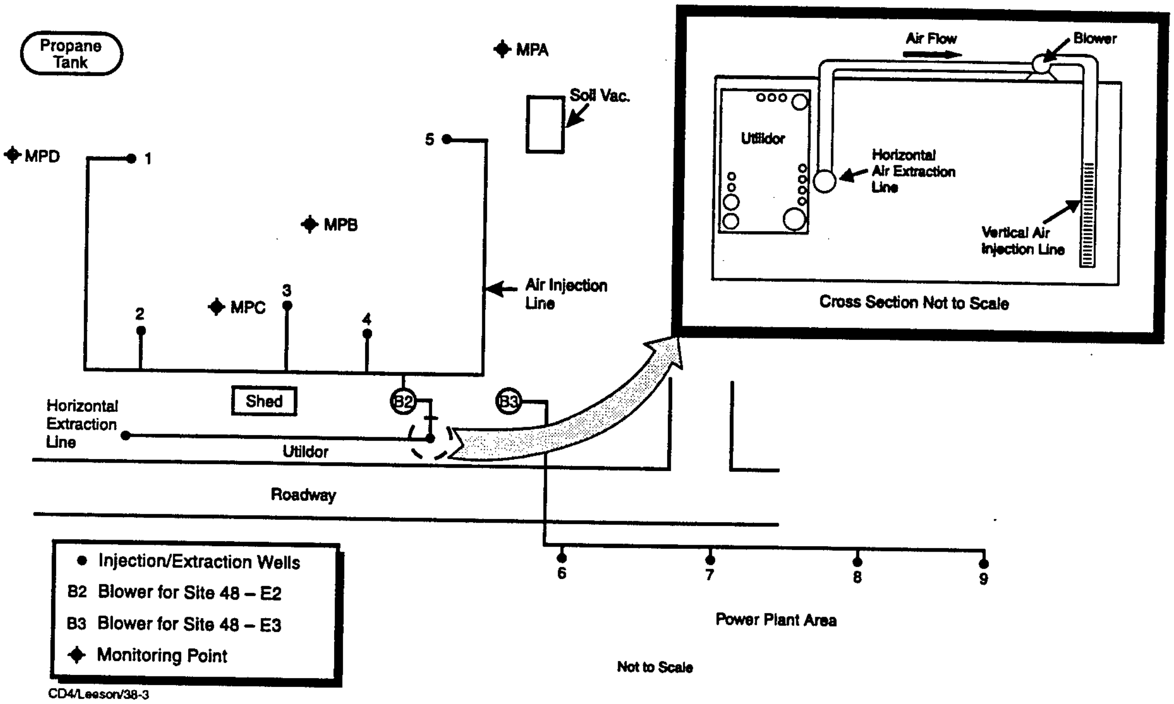

Figure 2-13. Soil Gas Extraction to Isolate a Subsurface Structure at Site 48, Eielson AFB, Alaska

The flowrate selected from this calculation must be confirmed during bioventing system operation 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 to 2%. To ensure adequate oxygen levels in the entire treatment cell, a minimum level of 5% should be maintained.

2.3 Well Spacing

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

- Based on 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 probably is the fastest method. It normally is done by plotting the log of pressure versus distance as described in Section 1.5.3. The limitation to this approach is that it incorporates only one of the three factors that affect the radius of influence. In order to determine more exactly the radius of oxygen influence, air flowrate and oxygen utilization must be considered. In low-permeability soils, a pressure effect may be seen in a monitoring point, but air flowrates to that point may be too low to supply adequate oxygen. Conversely, in a high-permeability soil, air flowrates sufficient to supply oxygen may occur at pressure differentials that cannot be measured. It has been our experience that, if a pressure criteria 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 for a given air flowrate can be estimated 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 can be used:

$$R_I = \sqrt{\frac{Q(20.9\% - 5\%)}{\pi\ h\ k_o\ \theta_a}} \tag{2-2}$$

where: R_I = radius of influence (ft)

Q = air flowrate (ft^3/day)

$20.9 - 5\%$ = oxygen %

k_o = oxygen utilization rate (%/day)

θa = air filled porosity (cm^3_{air}/cm^3_{soil})

h = aerated thickness (ft)

Example 2-3. Calculation of Radius of Influence: To calculate the radius of influence at Dover AFB, Equation (2-2) 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)

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

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

In practice, it is best 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. We have never encountered 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 at a minimum, several days are 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 airflow patterns. In theory, airflow lines may develop such that "dead zones" are created. However, given vertical and horizontal flow paths and diffusion, these dead zones are unlikely to occur, and we do not recommend routinely compensating for them.

2.4 Blowers and Blower Sizing

A blower provides the driving force to move air through the bioventing system. In selecting the blower size, one must consider the required air flowrate and the total system pressure drop. System pressure drop includes (1) the backpressure 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 (2) 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 for illustration purposes.

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 airflow requirement and the suction and discharge pressures presented to the blower during operation at the design air flowrate. Centrifugal blowers generally are favored when air flow requirements are high and/or the system pressure drop is low. Rotating positive displacement blowers generally provide lower airflow capacity and higher pressures than centrifugal blowers, but can generate moderate-to-high vacuum at the blower inlet. Due to their vacuum capability, rotating positive displacement blowers may be used for systems operating in an extraction configuration. Reciprocating positive displacement machines typically are used for applications requiring very high pressure. Except for single action diaphragm pumps used for soil gas sampling, reciprocating positive displacement pumps rarely are used in bioventing applications and are not discussed further. The required pressure or

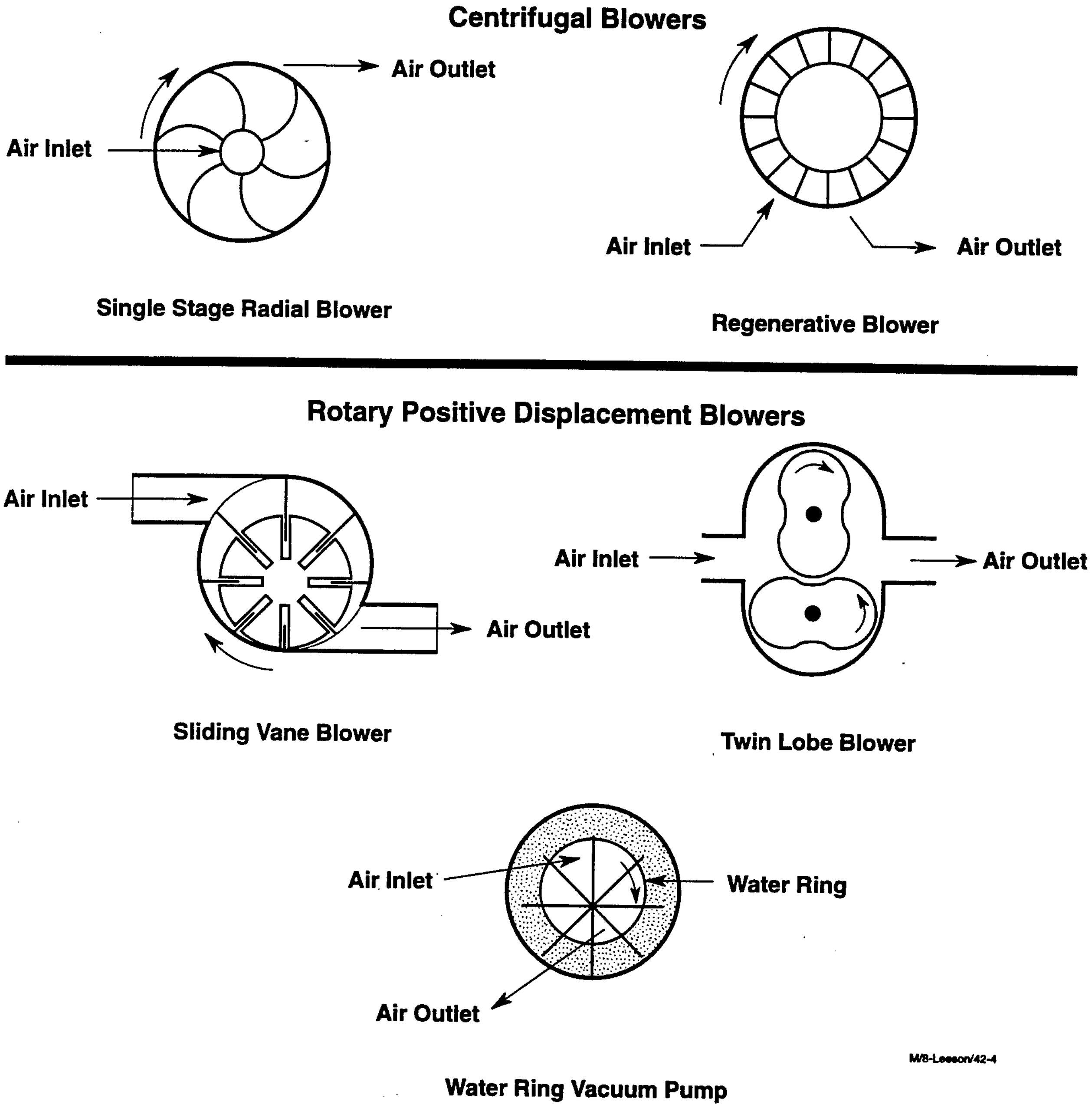

Figure 2-14. Schematic Diagram of Blower Types

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 kinetic energy to the air stream by means of a rapidly rotating impeller or propeller. Part of the added kinetic energy then is 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 enters the volute casing where the air velocity drops, converting kinetic energy into pressure head.

Regenerative centrifugal blowers provide efficient air movement in the flowrate 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 blower, 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. As the fast-moving air leaves the blade tip, it flows around the housing contour and back down to the base of the next blade where the flow pattern is repeated. 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 in comparison 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 airflow capacity to act as the air handler in a bioventing system. Lobe blowers and water ring vacuum pumps have both seen some service 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 are mounted on parallel shafts and 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 is formed on the inside of the pump casing by the rotary action of the impeller. Since 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 airflow at the necessary pressure and that it operates properly. Choosing the wrong blower can result in an inability to deliver sufficient oxygen or a significantly shortened blower life. It is best to select the blower to allow 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 its life. Selection of an oversized blower reduces operating efficiency and increases capital costs unnecessarily. 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, we will need to deliver 16 cfm (453 L/min) of air 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 as the blower of choice because it operates efficiently at the specified flowrate and pressure. Blower performance curves were obtained for three different size blowers (0.1, 0.125, and 2.5 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 that shows how to select and size a blower for use in bioventing. Situations in the field may become more complicated if there are significant seasonal variations in soil gas permeability or other parameters affecting gas flow and oxygen demand. The key design consideration is to select and size a blower for the most demanding conditions, i.e., when oxygen demand is highest and soil gas permeability is lowest. Incorporating a bypass into the system plumbing will allow for reducing airflow delivered to the soil. 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) and *Pump Handbook* (Karassik et al., 1991)[1].

2.5 Vent Well Construction

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

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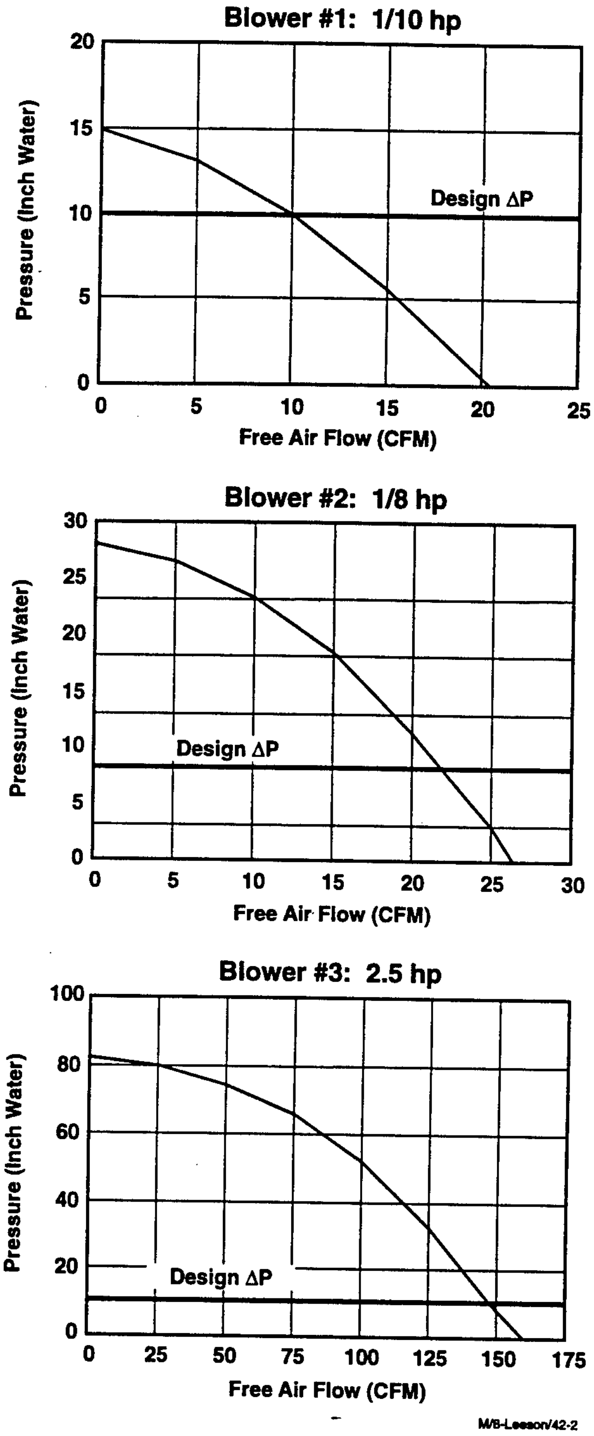
[1] Refer to Appendix B for recommended specifications and manufacturers for the blowers.



Blower #1: 1/10 hp

Blower #2: 1/8 hp

Blower #3: 2.5 hp

Figure 2-15. Performance Curves for Three Different Size Blowers (1/10, 1/8, and 2.5 hp, respectively)

The diameter of the vent well typically is between 2 and 4 inches (5.1 to 10 cm), although larger and smaller diameters have been used successfully. Vent well diameter will depend on the soil type, ease of drilling, and the area and depth of the contaminated volume. In most shallow or sandy soils, a 2-inch-diameter (5.1-cm) vent well will provide adequate airflow for bioventing. For sites with contamination extending below 30 ft (9.1 m) or in low permeability soils, a 3- or 4-inch (7.6- or 10-cm) vent well is recommended since this will allow for greater airflow to aerate a greater volume. As the well depths increase, the fractional cost of well-construction materials per ft of well decrease significantly[1].

The vent well typically is constructed of schedule 40 polyvinyl chloride (PVC), and should be screened with a slot size that maximizes airflow 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 the screen for an extraction well, the potential for water table upconing must be taken into account. 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 it is necessary to screen below the water table, additional screened length above the water table may be necessary to offset water table upconing.

Hollow-stem auguring 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 also are appropriate. In shallow, softer soils, hand-auguring may be feasible. Whenever 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 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.

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, we would 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

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[1] Refer to Appendix B for recommended specifications and manufacturers for the vent well construction materials.

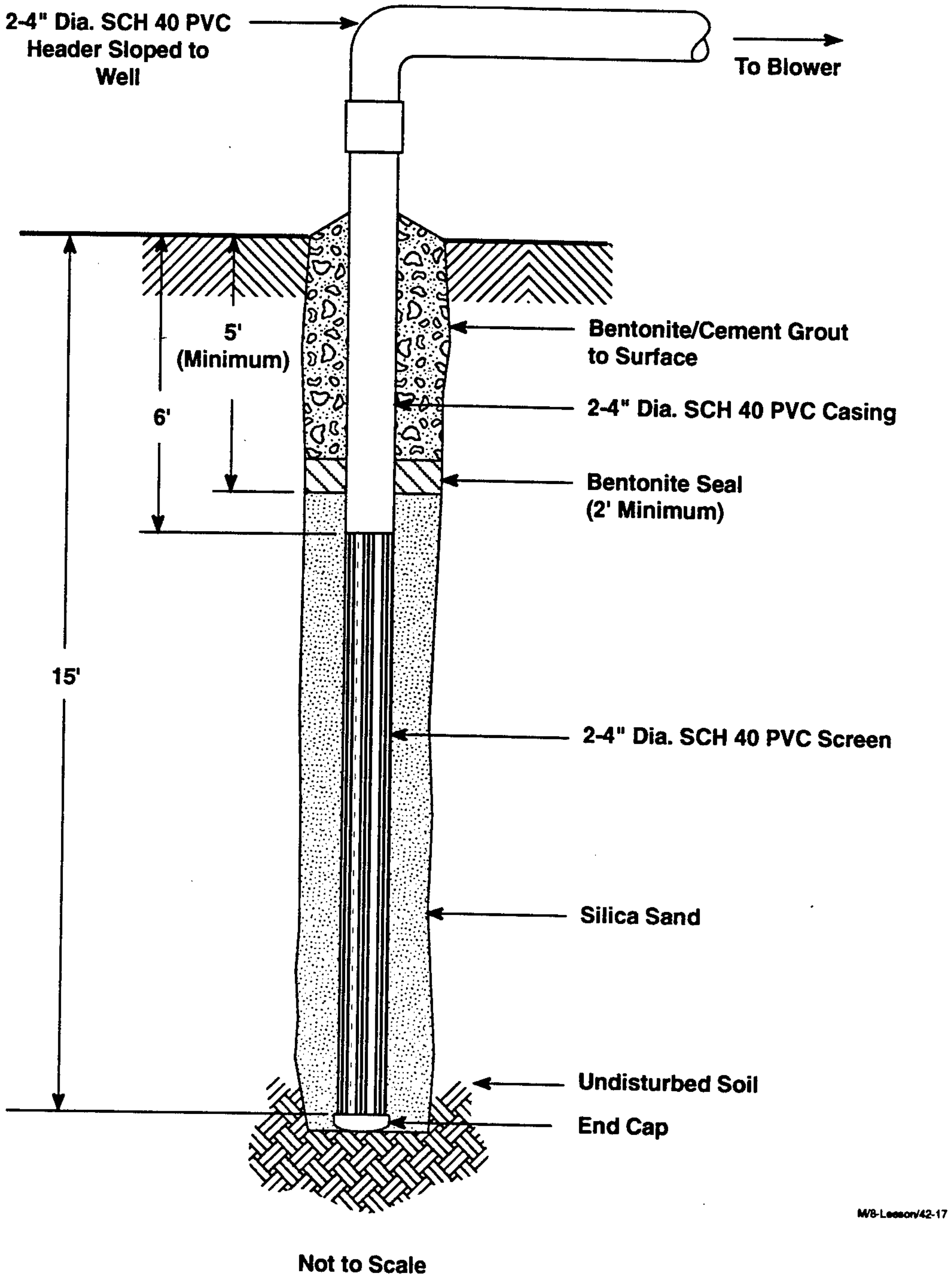

Figure 2-16. Schematic Diagram of a Typical Vent Well Construction

wells to ensure that a good seal has been obtained. Injection wells should be installed with a bentonite-and-grout slurry. Dry bentonite chips do not provide an adequate seal unless the chips are hydrated continuously 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, monitoring points should be located with consideration given to 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 will 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 to 3 ft (0.61 to 0.91 m) above the water table if 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 will be 3 to 5 ft (0.91 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 one-fourth of the vent well screen. In some cases, it may be desirable to add additional screened depths to more fully monitor the contaminated interval, to monitor differing stratigraphic intervals, or to adequately monitor deeper sites with broadly screened vent wells.

Table 2-3. Recommended Spacing for Monitoring Points

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

[1] This assumes 10 ft of vent well screen. If more screen is used, the >15-ft spacing should be used.

[2] Monitoring point intervals are based on a venting flowrate range of 1 cfm per ft of screened interval for clays and up to 3 cfm per ft of screened interval for coarse sands.

Example 2-5. Selection of Depth Intervals for Monitoring Points: Site soils are sandy with groundwater at 30 ft (9.1 m). The vent well was screened from 17.5 to 27.5 ft (5.3 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 will vary depending on the drilling depth and technique. The monitoring points consist of a small-diameter (¼-inch [0.64 cm]) tube to the specified depth, with a screen approximately 6 inches (15 cm) long and 1 inch (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 to 2 ft (0.30 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[1].

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 to 25% range, and for hydrocarbons greater than 100 ppmv. The tubing material must have sufficient strength and be nonreactive, appropriate materials 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. However, this normally will not be the case.

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[1] Refer to Appendix B for recommended specifications and manufacturers for monitoring point construction materials.

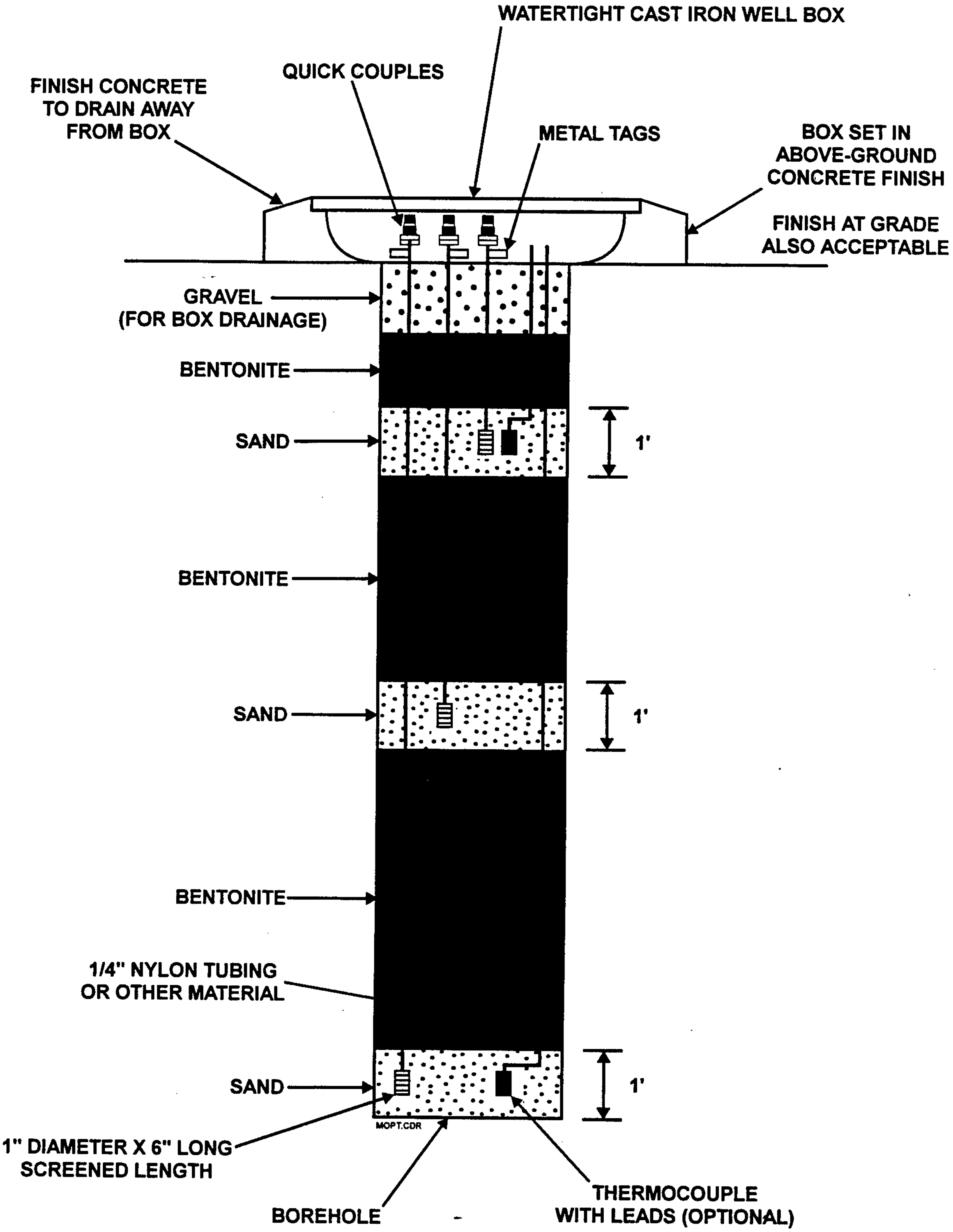

Figure 2-17. Schematic Diagram of a Typical Monitoring Point Construction

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 the 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 are biodegraded 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.

3.0 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 sampling, in situ respiration testing, biodegradation and volatilization quantification, surface emissions measurement, optional monitoring, and operation and maintenance of the bioventing system. These methods are discussed in Sections 3.1 through 3.5.

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, the 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 it is not possible to conduct an in situ respiration test during different seasons, then it should be conducted under similar conditions as the initial test. Due to 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 site remediation progresses and contaminant concentrations are reduced, in situ respiration rates should approach those measured in the uncontaminated area. It is not necessary to conduct frequent in situ respiration tests. 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

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[1] Refer to Sections 1.2 (Soil Gas Survey) and 1.4 (In Situ Respiration Testing) for more detail on sampling and analyzing soil gases.

[2] Refer to Section 1.4 (In Situ Respiration Testing) for additional detail.

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 when the in situ respiration rate in the contaminated area is similar to that in the uncontaminated area. In situ respiration testing to determine remediation success is preferable economically to relying on soil sampling as the sole indicator of site remediation, because it eliminates 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 one year) changes. Over longer periods, contaminant reduction will reduce rates. One phenomenon frequently observed is a substantial decline in rates from the initial in situ respiration rates to subsequent measurements. It appears that this generally is due to placement of monitoring points in less-contaminated soils. NAPL contamination usually is distributed in a very heterogeneous manner. Under nonventing conditions, volatilization will spread hydrocarbons in soil gas resulting in more heterogeneous contamination. However, the soil contaminated in this fashion has a much lower total concentration because the sorbed hydrocarbons are present at much lower levels than in soils that actually contain NAPLs. If a monitoring point is placed in soil having 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. It is difficult to eliminate this problem, but it can be limited by attempting to place monitoring points in the most highly contaminated soil.

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 in order to provide these data. It should be noted, however, that in the case of injection mode systems, reconfiguration to extraction mode will provide an overestimate of the mass of hydrocarbons volatilized because the size of the in situ bioreactor is reduced[1].

The mass of hydrocarbons volatilized can be calculated as follows:

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

where: HC_{vol} = Mass of hydrocarbons volatilized (kg/day)

$C_{V,HC}$ = Concentration of hydrocarbons in extracted off-gas (ppmv)

Q = Flowrate (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:

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

where: HC_{bio} = Mass of hydrocarbons biodegraded (kg/day)

$C_{V,bkgd}$ = Concentration of oxygen in background, uncontaminated area (%)

$C_{V,O2}$ = Concentration of oxygen in extracted off-gas (%)

C = Mass ratio of hydrocarbon to oxygen degraded based on stoichiometry[2] (1/3.5)

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[1] Refer to Section 2.1 for a discussion of these issues.

[2] Refer to Section 1.4.2 for a discussion of stoichiometry.

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% and 140 ppmv, respectively. The system is operating at a flowrate of 4 cfm (113 L/min). Background oxygen concentrations are consistently at 20.9%. We first wish to calculate the mass of hydrocarbons volatilized.

Given the following parameters:

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

Using Equation (3-1):

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

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

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

$$HC_{bio} = \left(\frac{20.9\ -\ 19.0}{100}\right)\left(4\frac{\text{ft}^3}{\text{min}} \times \frac{28.3\text{L}}{\text{ft}^3}\right)\left(\frac{1\ \text{g HC}}{3.5\ \text{g O}_2}\right)\left(0.042\frac{\text{mole}}{\text{L}}\right)\left(32\frac{\text{g}}{\text{mole}}\right)\left(\frac{\text{kg}}{1{,}000\text{g}}\right)\left(\frac{1{,}440\ \text{min}}{\text{day}}\right)$$

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.

The fraction of total removal by biodegradation will be larger for injection systems because the opportunity for biodegradation is greater. In an injection mode, the vapors are pushed through the contaminated zone into the uncontaminated zone, allowing for additional biodegradation. However, when the system is operated in extraction mode, 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 5 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 due to low air flowrates, possible surface emissions often are a regulatory concern and surface emission rates may need to be quantified in order to obtain regulatory approval for bioventing. However, it should be noted that, according to the U.S. EPA document *Estimation of Air Impacts for Bioventing Systems Used at Superfund Sites* (U.S. EPA, 1993, EPA 451/R-93-003), emissions from bioventing sites operating in an injection mode are thought to be minimal. Therefore, they are not discussed in this document.

One standard surface emission sampling protocol using isolation flux chamber procedures is described in Dupont and Reineman (1986) and Dupont (1988) 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 supply 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 a zero pressure is being maintained on the entire system.

In all cases, a totally inert system is employed. Teflon™ tubing and stainless steel fittings assure that there is no 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 (McVeety, 1991):

$$F = \frac{C_V V_{\bar{r}}}{A} \tag{3-3}$$

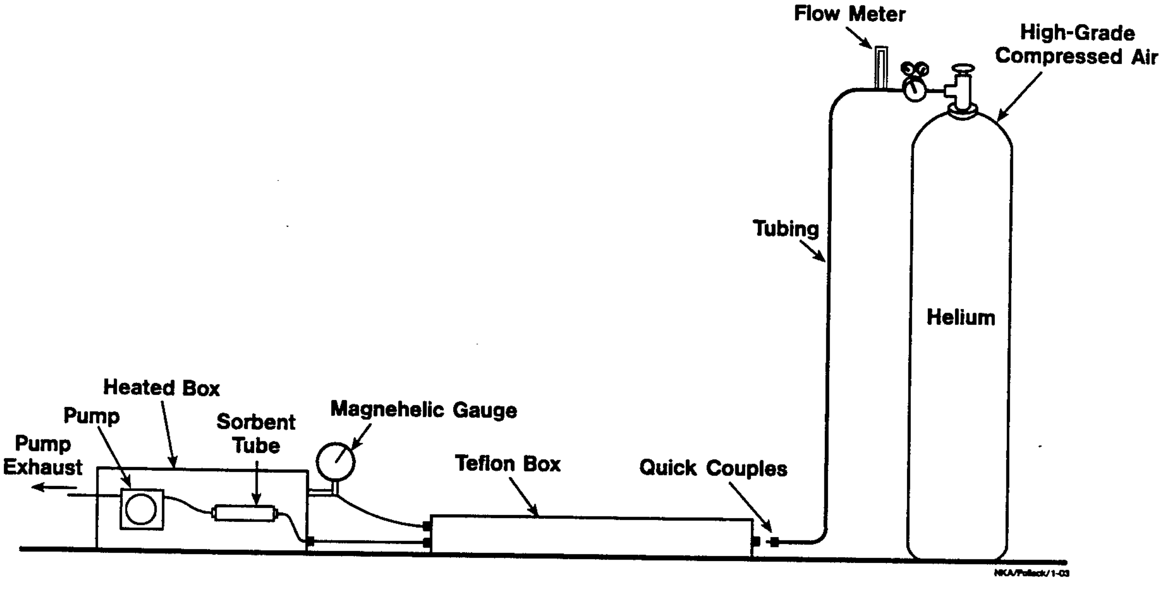


Figure 3-1. Schematic Diagram of a Surface Emissions Monitoring Device

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

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

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

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

At bioventing sites where surface emissions have been measured, BTEX and TPH surface emission rates have been several orders of magnitude below regulatory levels. 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. These results provide strong support for continued operation of bioventing systems in injection mode.

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, D.C.	Diesel Spill	10 - 15	20	5,100	0.44
Eielson AFB, AK	JP-4 Spill	6.5 - 13	30.0	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

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 be conducted only 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 in an injection mode, a simple visual system check to ensure that the blower is operating within its intended flowrate, pressure, and temperature range is required. Weekly system checks are desirable. These system checks often can be conducted by someone on site 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. Any off-gas treatment system also will 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). Of the 125 blowers installed to date under the Bioventing Initiative, only three have required repair or replacement.

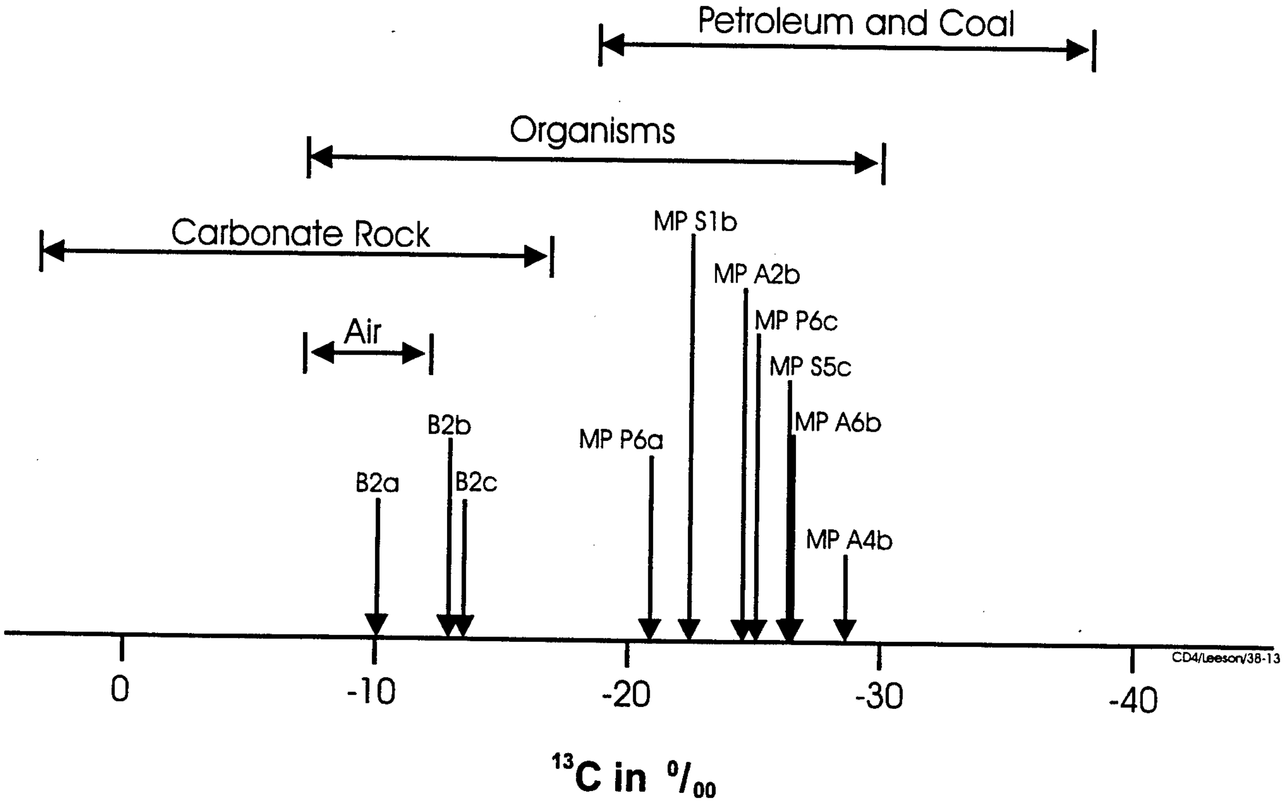


Figure 3-2. Carbon Isotopic Compositions of Soil Gas Carbon Dioxide at Site 20, Eielson AFB, Alaska, August 1993

4.0 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 will approach background respiration rates. When the in situ respiration rate in the contaminated area approaches that in the uncontaminated area, this is a good indication that the site is remediated and final soil sampling can be conducted. Initially, one can estimate the time necessary for cleanup of the site based on in situ respiration rates as shown in Example 4-1.

Example 4-1. Calculation of Remediation Time Based on In Situ Respiration Rates: For this example, we assume an average oxygen utilization rate of 6% O_2/day and an initial average soil concentration of 6,000 mg TPH/kg soil. Oxygen utilization is related to hydrocarbon degradation by the following equations:

$$C_6H_{14} + 9.5O_2 \rightarrow 6CO_2 + 7H_2O \tag{4-1}$$

$$k_B = -0.68\ k_o \tag{4-2}$$

Using the above assumptions, an oxygen utilization rate of 6% O_2/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:

$$\frac{C_o}{k_B} = \text{Cleanup time} \tag{4-3}$$

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

This calculation provides a reasonable "ball park" 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 period. Due to 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. Due to 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 to 99% cleanup. The amount of soil sampling conducted at a site has a tremendous impact on the cost of the project. Minimizing soil sampling will make a remediation effort much more cost effective. With bioventing systems, in situ respiration testing can indicate when the site is clean and therefore when to collect final soil samples. The number of final soil samples collected usually is driven by regulatory issues. The Department of Natural Resources of the State of Michigan published a guidance document for verification of soil remediation. This document provides several methods for statistical sampling strategies (Department of Natural Resources, MI, 1994). This document provides information on design of the sampling grid and determination of the upper confidence limit (UCL) of the final mean. The upper confidence limit is calculated from the following equation:

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

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

$$S_X = \frac{S}{\sqrt{n}} \tag{4-5}$$

where: S = standard deviation

n = sample size

If the calculated upper confidence limit is higher than the regulatory threshold, than the lambda relationship is used to calculate the appropriate sample size:

$$\lambda = \frac{RT - \overline{X}}{S} \tag{4-6}$$

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, as 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:

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

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.

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

	Level for t test									
Single-sided Double-sided	$\alpha = 0.01$ $\alpha = 0.02$					*$\alpha = 0.05$* $\alpha = 0.10$				
λ	β 0.01	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

$$\lambda = \frac{100 - 90}{30} = 0.33$$

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

An alternative method for estimating final sample size is provided by Ott (1984). This method determines the number of soil samples required to show a statistical difference between initial and final contaminant concentrations.

$$n = \frac{\sigma^2 (z_\alpha + z_\beta)^2}{(\mu_o - \mu)^2} \qquad (4\text{-}7)$$

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.

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

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 has been operating for 3.5 years, we can estimate the final mean TPH concentration as follows:

$$4.1 \text{ mg/kg-day} \times 1{,}278 \text{ days} = 5{,}240 \text{ mg/kg TPH degraded}$$

$$\text{Estimated final[TPH]} = 6{,}000 \text{ mg/kg} - 5{,}240 \text{ mg/kg} = 760 \text{ mg/kg}$$

Using this estimate of the final mean TPH concentration, the number of samples needed to provide statistically significant data can be calculated. Using Equation (4-7) and the following parameters:

σ = $(8{,}000)^2$
z_α = 1.645 (for $\alpha = 0.05$)
z_β = 2.33 (for $\beta = 0.01$)
μ_0 = 6,000 mg/kg
μ = 525 mg/kg

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

$$n = \frac{(8{,}000)^2(1.645 + 2.33)^2}{(6{,}000 - 760)^2}$$

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)[1]

z	.00	.01	.02	**.03**	*.04*	*.05*
0.0	.0000	.0040	.0080	.0120	.0160	.0199
0.1	.0398	.0438	.0478	.0517	.0557	.0596
0.2	.0793	.0832	.0871	.0910	.0948	.0987
0.3	.1179	.1217	.1255	.1293	.1331	.1368
0.4	.1554	.1591	.1628	.1664	.1700	.1736
0.5	.1915	.1950	.1985	.2019	.2054	.2088
0.6	.2257	.2291	.2324	.2357	.2398	.2422
0.7	.2580	.2611	.2642	.2673	.2704	.2734
0.8	.2881	.2910	.2939	.2967	.2995	.3023
0.9	.3159	.3186	.3212	.3238	.3264	.3289
1.0	.3413	.3438	.3461	.3485	.3508	.3531
1.1	.3643	.3665	.3686	.3708	.3729	.3749
1.2	.3849	.3869	.3888	.3907	.3925	.3944
1.3	.4032	.4049	.4066	.4082	.4099	.4115
1.4	.4192	.4207	.4222	.4236	.4251	.4265
1.5	.4332	.4345	.4357	.4370	.4382	.4394
1.6	.4452	.4463	.4474	.4484	*.4495*	*.4505*
1.7	.4554	.4564	.4573	.4582	.4591	.4599
1.8	.4641	.4649	.4656	.4664	.4671	.4678
1.9	.4731	.4719	.4726	.4732	.4738	.4744
2.0	.4772	.4778	.4783	.4788	.4793	.4798
2.1	.4821	.4826	.4830	.4734	.4838	.4842
2.2	.4861	.4864	.4868	.4871	.4875	.4878
2.3	.4893	.4896	.4898	**.4901**	.4904	.4906
2.4	.4918	.4920	.4922	.4925	.4927	.4829
2.5	.4938	.4940	.4941	.4943	.4945	.4846

[1] Bolded areas correspond to determining z_β. Italicized areas correspond to determining z_α.

5.0 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 cubic yard (Downey et al., 1994b). At sites with over 10,000 cubic yards of contaminated soil, costs of less than $10 per cubic yard have been achieved. Costs greater than $60 per cubic yard are associated with smaller sites, but bioventing still can offer significant advantages over more disruptive excavation options. Operation and maintenance costs are minimal, particularly when on-site personnel perform the simple system checks and routine maintenance that are needed. Table 5-1 provides a detailed cost breakdown of remediation of 5,000 cubic yards 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 to other in situ bioremediation technologies (Table 5-2). Costs shown in Table 5-2 reflect actual costs for these three technologies at fuel spills at 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 JP-4 jet fuel per kg of soil. Costs are provided for the following remediation scenarios: two years of in situ bioventing; excavation and one year of on-base landfarming with leachate controls; one year of soil vapor extraction with thermal vapor treatment; 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[1]	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**

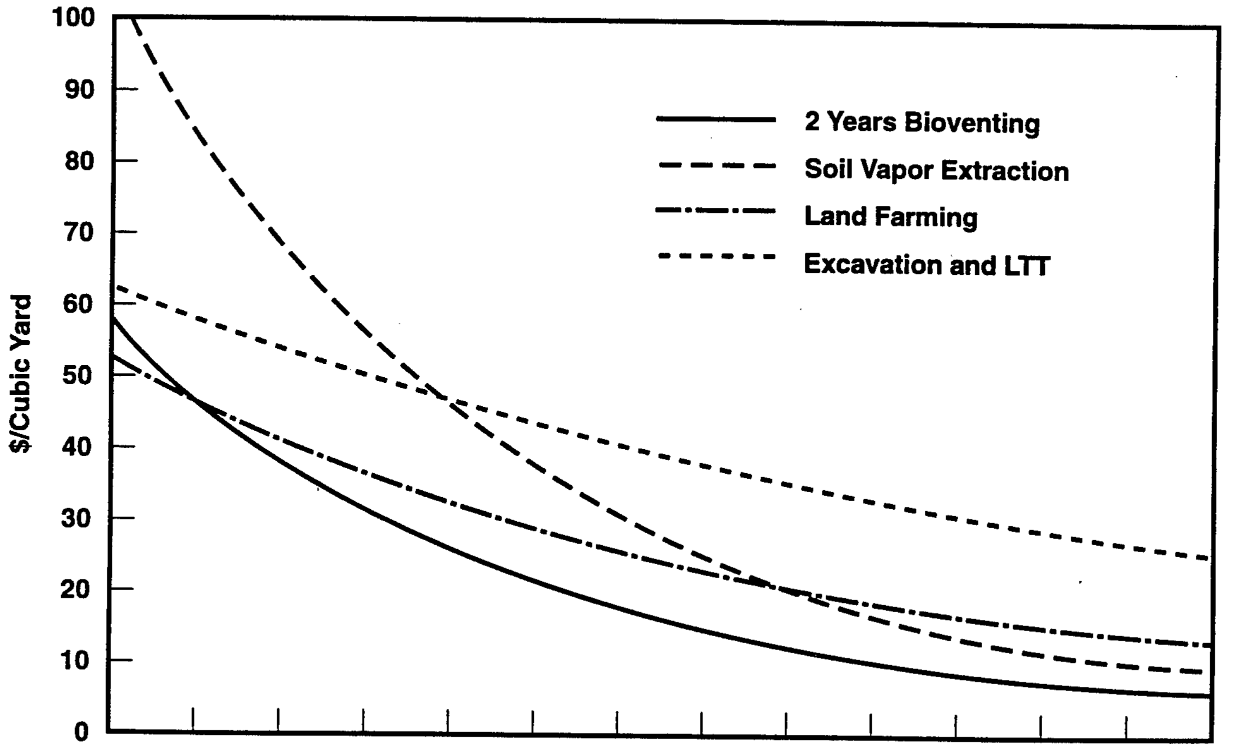
[1] Assumes four air injection wells drilled to a depth of 15 ft.

Table 5-2. Cost Comparison of In Situ Bioremediation Technologies Utilized at Fuel Spill Sites (Ward et al., 1992)

Task	Total Costs ($ per m^3 of Contaminated Earth)		
	Hydrogen Peroxide	Nitrate	Bioventing[1]
Construction[2]	45	118	26
Labor/Monitoring	72	96	40
Chemicals	500	30	0.44
Electricity	24	12	6.8
Total	**641**	**256**	**73**

[1] Values reflect only first 4 months of demonstration.

[2] Prorated to a 5-year service life on buildings, pumps, and blowers.



M/8-Lesson/42-14

Figure 5-1. Comparison of Costs for Various Remedial Technologies for Fuel-Contaminated Soils (Downey et al., 1994b)

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APPENDIX A

GLOSSARY

GLOSSARY

abiotic - not relating to living things, not alive

acidity - measure of the hydrogen ion concentration of a solution

adsorption - the process by which molecules collect on and adhere to the surface of an adsorbent solid due to 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 - general term for the 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 - a water-bearing layer of permeable rock, sand, or gravel

bentonite - clay composed of volcanic ash decomposition which is used to seal wells (hole plug)

bioavailability - a general term to describe the accessibility of contaminants to the degrading populations. Bioavailability consists of: (1) a physical aspect related to phase distribution and mass transfer, and (2) a physiological aspect related to the suitability of the contaminant as a substrate

biodegradable - a material or compound which is able to be broken down by natural processes of living things such as metabolization by microorganisms

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

biodegradation rate - the mass of contaminant metabolized by microorganisms per unit time. In soil contamination this is normalized to the mass of soil and is usually expressed as *mg contaminant degraded/kg soil-day* (mg/kg-day).

biofilm - a 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 the air and vapor contaminants pass through the filter, contaminants transfer from the gas phase to the biolayer where they are metabolized

biomass - the amount of living matter (in a specified area)

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

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

bioremediation - general term for the technology of using biological processes such as microbial metabolism to degrade soil and water contaminants and decontaminate sites

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

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

blower - equipment which produces a constant stream of forced air. Blowers are sized in terms of horsepower

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

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

catalyst - a substance which 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 - an incineration process which 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-dry

co-metabolic 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 due to 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, which diffuses across an area of 1 square centimeter in 1 second due to a unit concentration gradient, (particular to compound and medium pair)

electron acceptor - relatively oxidized compounds which take electrons from electron donors during cellular respiration resulting in the release of energy to the cell

electron donor - organic carbon, or reduced inorganic compounds, which give 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 - a microbial trait enabling aerobic or anaerobic respiration, depending on environment

first order reaction - a chemical reaction in which an increase (or decrease) in reactant concentration results in a proportional increase (or decrease) in the rate of the reaction

head - the pressure difference between two places, an energy term expressed in length units

immiscible - refers to liquids which do not form a single phase when mixed; e.g. oil and water

in situ - refers to a technology or treatment process which 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 - the process of injecting gas into a well to produce an in-well airlift pump effect

mineralization - the complete conversion of an organic compound to inorganic products (principally water and carbon dioxide)

miscible - refers to liquids which form a single phase when mixed; e.g. ethanol and water

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

nutrients - constituents required to support life and growth

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

oxidation - chemical process which 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 due to biological and chemical action

ozonation - the injection of ozone into a contaminated site

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

perched aquifer - unconfined groundwater separated from an underlying main body of groundwater by a low-permeability rock layer which blocks the 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 (UV) light

pore space - the 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 which provides the majority 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 and then treated off site before being returned

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

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

Raoult's law - physical chemical law which 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 which results in a net gain of electrons to an element or compound

remediation - activity involved with reducing the hazard from a contaminated site

respiration rate - see oxygen utilization rate sand - unconsolidated rock and mineral particles with diameters ranging from 1/16- to 2 mm

saturated zone - the layers of soil which lie below the groundwater table

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

soil vacuum extraction (SVE) - a process designed and operated to maximize the volatilization of low-molecular-weight compounds, with some biodegradation occurring soil gas permeability - a soil's capacity for fluid flow, varies according to grain size, soil uniformity, porosity, and moisture content

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

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

surfactant - substance which 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 groundwater, or other liquids or gases, from a well while producing a reduced pressure in the well

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

vent well - a well designed to facilitate injection or extraction of air to/from a contaminated soil area

volatile - easily vaporized at relatively low temperatures

volatilization - process of vaporizing a liquid into a gas

zero order reaction - a chemical reaction in which an increase (or decrease) in reactant concentration results in no change in the rate of reaction (as long as some reactant is present)

APPENDIX B

EQUIPMENT SPECIFICATIONS AND MANUFACTURERS

TABLE OF CONTENTS

The products and manufacturers listed in this document are intended as guidance for environmental managers and consulting engineers. Products or manufacturers are not endorsed by the U.S. Air Force or the U.S. Environmental Protection Agency.

1.0 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 of transparent Tedlar™ and has a polypropylene fitting. The bag is approximately 7×7 inches and is sold in packages of ten. 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, Inc., in 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 inches in length. Size of tubing is 1/4-inch-O.D. × 3/16-inch-I.D. and can be purchased from VWR Scientific.

Wire/Cable Ties

Nylon cable ties are used like a hose clamp to secure the latex tubing to the tedlar bag fitting. Cable ties can be purchased from Graingers or any hardware store. Catalog # 6X750, pack of 100, $1.91/pack.

Oxygen/Carbon Dioxide Gas Sampling Meter

This hand-held instrument has a rechargeable battery good up to sixteen hours. It has an oxygen and carbon dioxide range of 0 to 25%. 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 $3200.

Carrying Case for Gas Sampling Meter

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

The case is used to protect and carry 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 to 100% LEL and 0 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-hr 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 which replaces the Trace-Techtor™ meter.

The meter is sold by Cascade Associates in Youngstown, Ohio, (216) 758-6649. It costs approximately $1475.

1:1 Diluter

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

The function of the 1:1 diluter is to reduce the gas sample flow by one-half. This dilution will reduce the concentration by 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 be held in one hand. The diluter has two rotameters built into it to permit a dilution factor up to ten. A diluter is required when the oxygen levels of the gas sample drop below 12%, at which 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 at its highest setting.

The function of the 10:1 diluter is to reduce the gas sample flow up to a factor of ten. The dilution factor is set by adjusting the two rotameters until their ratio of the two flows is equal to the dilution ratio. This will reduce 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 hand-held instrument has a rechargeable battery good for ten hours. It is capable of measuring petroleum-based hydrocarbon vapors (BTEX) up to 10000 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 high reliability and preventive maintenance. 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 be equipped to detect methane or natural gas.

The meter is sold and manufactured by Gastech in Newark, California, (415) 794-1973. The price is approximately $1500. The Trace-Techtor is no longer manufactured.

Interface Probe

The probe is constructed in the shape of a disk which stores a 100-ft measuring tape and a sensor probe. It weighs sixteen pounds, is 16×18×6 inches, and is battery-operated. The interface probe resembles a common tape measure but is 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 $2000.

150-Ft Tape Measure

A 150-ft fiberglass reel tape is needed for site mapping during soil gas survey and also for measuring borehole depths and monitoring point construction. An appropriate measure is available from Graingers catalog #6C192, cost $57.70.

Soil Gas Probes and Well Points (The Macho System)

Electric-powered sampling systems are used for driving soil gas probes. The deluxe system includes a variable-speed hammer drill and the ability to sample soil gas to a depth of approximately ten ft. This is a good starter set, but we would recommend that additional shafts, slotted well points, and hollow probe nipples be purchased. The Macho System costs approximately $3,065 and is available from KVA Analytical Systems, Falmouth MA., (508) 540-0561.

Bulkhead Quick Coupler (Parker)

These brass fittings are threaded into the top of the soil gas probe after it is driven to the desired depth. The fittings allow the sampler an air-tight connection between the probe and the vacuum sampling pump then pulls the soil gas sample from the soil. A supplier is Forberg Scientific, Columbus, Ohio, (614) 294-4600.

Diaphragm Pump (Vacuum/Air Compressor)

The pumps are usually wired for 110 volts for the 1/16-, 1/8-, and 1/3-hp versions. The pumps and compressors are produced by Gast. They are preferred due to their reliability and ease for maintenance.

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

The pump is sold by Grainger in Columbus, Ohio, (800) 323-0620. The costs depend on the size of the pump. A 1/3-hp (catalog #4Z024) costs $228.00.

Probe Puller Adapter

The probe puller adaptor was made by Battelle staff. It is simply a piece of square steel tubing approximately 4 inches by 4 inches by 2 inches 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 to remove soil gas probes when sampling is completed. It is sold by Graingers (800) 323-0620, Catalog #5Z156, Cost $100.

Miscellaneous Supplies for Soil Gas Survey

Other supplies needed at the site 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 generator.

2.0 VENT WELL INSTALLATION EQUIPMENT

Contracted Drilling Services

If installation of the vent well and soil gas monitoring points is being done by a contracted driller, the driller will provide monitoring vent well and well construction materials (sand and bentonite). However, the soil gas monitoring points will need to be furnished to the driller. If no driller is used, the items in this section will need to be acquired.

Hand Augering and Soil Sampling Equipment

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

The core sampler is another way to obtain undisturbed soil samples. The slide hammer actually 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, Carrying Case

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

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

The metal carrying case is about six ft long and one ft tall and holds the complete auger, disassembled. It has a foam lining to protect contents during travel.

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

Brass Sleeves and Plastic End Caps

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

The sleeve is placed inside the auger head and used as a core sample liner. It contains the soil 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 is approximately $3 for both items.

PVC Well Screen

Well screen constructed of 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 available also in stainless steel.

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

PVC Riser

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

Bentonite Chips

The chips are available in coarse grades or small pellets. Common sizes include 0.375- and 0.75-inch chips or pellets. They are made from dry bentonite clay and sold in 50-pound bags. The bentonite is chemically stable and able to 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 located in Dayton, Ohio, (800) 777-0977. The price is approximately $10 for 50 pounds.

Silica Sand

The sand contains silica powder for increased chemical stabilization. It is commonly found in the 10×20 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 located in Dayton, Ohio, (800) 777-0977. The price is approximately $6 for 50 pounds.

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 located in Dayton, Ohio, (800) 777-0977. The price is approximately $4 for 50 pounds. 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 8 inch × 12 inch or 12 inch × 12 inch sizes and 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.

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

3.0 SOIL GAS MONITORING POINT EQUIPMENT

Contracted Drilling Services

If installation of the vent well and soil gas monitoring points is being done by a contracted driller, the driller will provide monitoring vent well and well construction materials (sand and bentonite). However the soil gas monitoring points will need to be furnished to the driller. If no driller is used, then items in this section will need to be acquired.

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

The core sampler is another way to obtain undisturbed soil samples. The slide hammer actually 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, Carrying Case

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

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

The metal carrying case is about six ft long and one ft tall and holds the complete auger, disassembled. It has a foam lining to protect contents during travel.

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

Brass Sleeves and Plastic End Caps

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

The sleeve is placed inside the auger head and used as a core sample liner. It contains the soil 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 is approximately $3 for both items.

Suction Strainer

The suction strainer resembles an oxygen diffuser used in fish tanks. It is approximately 0.75 inches in diameter and 8 inches long, constructed of a nylon frame with number 50 mesh screen to permit the flow of gases. The strainers must be tapped with ⅜-inch National Pipe Thread (NPT) in order to install the connector and nylon tubing.

The strainers are filled with aquarium gravel to ensure 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, where 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 from plastics and has an opening on the end for 0.25-inch tubing. The other end has 0.375-inch 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. They cost approximately $1.60 each.

Nylon Tubing

Often called Nylotube, it is made of nylon and sold in various colors for identification purposes. Most common applications of the tube involve the 0.25-inch 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 favored because it is inexpensive, is chemically resistant to hydrocarbons, and is available in many colors. However, the tubing will adsorb some small amount of hydrocarbons.

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. They also give 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, located in Columbus, Ohio, (614) 294-4600. A male connector costs approximately $6 and a female 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 ft.

The thermocouple is used to measure temperatures, often within a soil gas monitoring point or the 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 ft.

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 collection of temperature data.

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

Brass Tags

The tags are available in one- to two-inch 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 can also be used to label pipes, valves, etc.

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

Tag Stamping Kit

Stamping kits are sold in sizes from 0.125 to 0.5 inches. They contain both 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, New Haven, Connecticut, (800) 754-7360. The kit costs approximately $80.

Bentonite Chips

The chips are available in coarse grades or small pellets. Common sizes include 0.375- and 0.75-inch chips or pellets. They are made from dry bentonite clay and sold in 50-pound bags. The bentonite is chemically stable and able to 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 located in Dayton, Ohio, (800) 777-0977. The price is approximately $10 for 50 pounds.

Silica Sand

The sand contains silica powder for increased chemical stabilization. It is commonly found in the 10×20 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 located in Dayton, Ohio, (800) 777-0977. The price is approximately $6 for 50 pounds.

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 located in Dayton, Ohio, (800) 777-0977. The price is approximately $4 for 50 pounds. 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 8 inch × 12 inch or 12 inch × 12 inch sizes and 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.

An appropriate manhole is sold by Environmental Well Products Company located 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 for measuring borehole depths and during monitoring point sand and bentonite additions. An appropriate tape is sold by Graingers, catalog #6C192, cost $57.70.

Miscellaneous

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

4.0 AIR PERMEABILITY TEST EQUIPMENT

Portable Generator

Several brands are available, and one with a maximum of 5500 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, but the larger ones have diesel engines.

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

The generator is sold by Grainger in Columbus, Ohio, (800) 323-0620. It costs approximately $2200.

Blowers

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

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

The blower is sold by Isaacs in Columbus, Ohio, (614) 885-8540. The blower costs vary according to size and power. Example: 2-hp, 145-cfm open flow, cost of $1,100.

Rotameters/Flowmeters

Flowmeters measure the rate at which a gas or liquid is flowing. Rotameters are transparent flowmeters that have the added ability to regulate the flow. The tubes may be constructed of 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 and flowmeter is manufactured and sold by King Instrument Company in Huntington Beach, California, (714) 841-3663. The prices vary as to which type is needed, but are generally $100 to $200.

Fluke Thermocouple Thermometer

This hand-held, 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-v 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 thermometer is supplied by several companies including Grainger in Columbus, Ohio, (800) 323-0620. It costs approximately $200.

Dwyer Magnehelic™ Gauges

Magnehelic gauges are used to record 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. Appropriate gauges are sold by Graingers, (800) 323-0620, Catalog #3T314, 3T317, 3T319, and 3T321. The cost for each gauge is approximately $51.00.

5-Way Valves (Swagelok®)

The 5-way valve is installed on the magnehelic gauge panel and gives the sampler the ability to record pressures from three points, one after another, simply by turning the valve handle. Sold by Scioto Valve, (614) 891-2617, Part No. B-43ZF2, the valve costs approximately $90.00

Male Non-Valved Quick Couple Plug (Parker®)

Fitting is connected to tubing from 5-way valve. This plug simply plugs into the fitting which is attached to a soil gas monitoring point for measuring pressure during the test. Supplied by Forberg Scientific (614) 294-4600, Part No. 4Z-Q4P-B, Cost $6.00

Stopwatches

A stopwatch is needed by 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 goods stores or at Radio Shack. Cost is about $20.00

5.0 IN SITU RESPIRATION TEST EQUIPMENT

Portable Generator

Several brands are available, and one with a maximum of 5500 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, but the larger ones have diesel engines.

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

The generator is sold by Grainger in Columbus, Ohio, (800) 323-0620. It costs approximately $2200.

Diaphragm Pump (Vacuum/Air Compressor)

The pumps are usually wired for 110 volts for the 1/16-, 1/8-, and 1/3-hp versions. The pumps and compressors are produced by Gast. They are preferred due to their reliability and ease of maintenance.

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

The pump is sold by Grainger in Columbus, Ohio, (800) 323-0620. The costs depend on the size of the pump, the 1/3-hp (catalog #4Z024) costs $228.00.

Rotameters/Flowmeters

Rotameters are transparent flowmeters with the ability to regulate the flow. The tubes may be constructed of plastic or glass. Each end has a female pipe thread made from brass or plastic. The rotameters will indicate the rate at which the gas is flowing. The flow meter used for in situ respiration testing is connected to the backside of a ⅓-hp diaphragm pump. The flow meter used is normally a 0.4 to 4.0 scfm sold by King Instruments Co. (714) 841-3663. Cost is generally $48.

Helium Leak Detector

The helium leak detector is a rechargeable instrument that can detect helium at concentrations from 0.01 to 100 percent. It operates in a three-stage process, where the sample enters the portable instrument, is analyzed, then purged to the atmosphere. The helium leak detector is approximately 14 inches × 12 inches × 5 inches and weighs seven pounds. The instrument must be calibrated with helium gas.

The helium leak detector is used to detect the presence of helium gas, which 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, Inc., 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 at approximately 2% helium for the in situ respiration test. Helium can be purchased from compressed gas suppliers or a welding supply. Cost per cylinder is $60.00.

Helium Cylinder Regulator

A two-stage cylinder regulator is necessary for connecting and dispensing the compressed helium gas. The correct connector for cylinder to regulator is a GA 580. Regulators can be purchased through the compressed gas supplier. Cost is approximately $180.00.

Helium/Air Mixing Manifold

The 2% helium mix in air is accomplished by using a one-inch-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 six inches 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 the concentration is too high or low, it can be adjusted 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 7 inches × 7 inches and is sold in packages of ten. 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, Inc., in Eighty Four, Pennsylvania, (800) 752-8472. The cost is approximately $82 for 10 bags.

Fluke Thermocouple Thermometer

This hand-held, 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-v 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 thermometer 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 flowmeters for air injection. When flow is recorded, the pressure needs to be recorded as well. Vacuum gauges are used on the diaphragm pump used to withdraw soil gas samples from monitoring points and simultaneously record the vacuum. Sold by Graingers (800) 323-0620, the cost is less than $20.00 per gauge, Catalog #1A318.

Oxygen/Carbon Dioxide Gas Sampling Meter

This hand-held instrument has a rechargeable battery good up to 16 hr. It has an oxygen and carbon dioxide range of 0 to 25%. 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 $3200.

Carrying Case for Gas Sampling Meter

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

The case is used to protect and carry 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 to 100% LEL and 0 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-hr 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 which replaces the Trace-Techtor™ meter.

The meter is sold by Cascade Associates in Youngstown, Ohio, (216) 758-6649. It costs approximately $1475. To find the nearest distributor for 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 three inches long. A diluter is required when the oxygen levels of the gas sample drop below 12%. At this low oxygen level, the platinum catalyst is not able to combust the gas sample properly.

The function of the 1:1 diluter is to reduce the gas sample flow by one-half. This dilution will reduce the concentration by 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 be held in one hand. The diluter has two rotameters built into it to permit a dilution factor up to ten. A diluter is required when the oxygen levels of the gas sample drop below 12%, at which levels 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 at its highest setting.

The function of the 10:1 diluter is to reduce the gas sample flow up to a factor of ten. The dilution factor is set by adjusting the two rotameters until their ratio of the two flows is equal to the dilution ratio. This will reduce 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.

6.0 MISCELLANEOUS ITEMS

Teflon™ Thread Tape

The white tape is made of Teflon™ and comes in rolls of 0.25-, 0.5- and 1-inch 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 inches. Most piping used is schedule 40 and in 10- or 20-ft lengths. Some of the supplies (e.g., 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. Costs depend on the specific piping size, length, and schedule required.

PVC Pipe Cement and Primer

The PVC primer is a volatile, clear liquid that is applied with a small sponge. The PVC cement is a viscous and gray liquid also applied with a sponge. Both have a strong odor and can be harmful if 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 sets quickly.

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

Pipe Fittings

Many different types and sizes of pipe fitting are needed for pump connections and tubing connections. The Graingers catalog shows a large selection of reasonably priced steel and brass pipe fittings.

7.0 OPTIONAL ITEMS

Soil Moisture Meter

The soil moisture meter is an electronic, hand-held instrument that operates from a 9-v battery. Two spring terminals at the top of the meter are used to connect the moisture blocks.

The meter gives a digital display of the soil moisture content as 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

The blocks consist of a lead wire connected to the gypsum block, which is a 1-inch-diameter cylinder. The blocks have a life expectancy of 3 to 5 yrs. The gypsum is able to compensate for varying salinity conditions.

They 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 in 1- to 4-ft lengths. Teflon™ is preferred for its chemically inert properties and low cost.

The bailers are lowered into the wells by cords or rope to remove water or other standing liquids. The well must be dry to install the screens and suction strainers. No soil gas sampling can occur due if liquid(s) are present.

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

APPENDIX C

EXAMPLE PROCEDURES FOR CONDUCTING BIOVENTING TREATABILITY STUDIES

TABLE OF CONTENTS

Example Procedure

For

Collection, Labeling, Packing, and Shipping of Soil Samples

1/2. Scope/Purpose

This procedure describes collection, labeling, packing, and shipping of soil samples as well as decontamination procedures for sampling equipment.

3. References

None.

4. Definitions

Sampling Team: People responsible for collecting and processing soil samples.

5. Procedure

5.1 Sample Collection

Soil samples usually are collected with split-spoon samplers during soil-boring operations or with hand-held soil augers. Regardless of how samples are collected, all equipment will be decontaminated prior to and after collection of each sample.

5.1.1 Equipment Decontamination

a. The sampler will be washed thoroughly.

b. Rinsed with deionized or distilled water.

c. Rinsed with methanol and allowed to air dry.

d. Rinsates will be disposed of in an environmentally sound manner.

5.1.2 Sample Collection

a. At a minimum, rubber or vinyl gloves will be worn to collect the sample. If higher levels of contamination are anticipated, nitrile or nitrocellulose gloves will be worn in addition to other appropriate safety gear as indicated in the Site Health and Safety Plan.

b. 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.

c. For split-spoon sampling, the soil core usually is 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.

d. If the soil is to be transferred to other containers, such as those listed below for various analysis types, scoop the sample directly into the sample container. If organic analyses are to be performed, the scoop should be stainless steel. A soil core sample will be spooned or scooped directly from the coring tube, split spoon, etc. into the sample container.

e. If a gloved hand comes into contact with the sample, then new gloves will be used for each sample. In addition, a background sample that contacts a glove will be collected as a control.

5.1.3 Split Samples

A homogenous 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. However, if a sample is collected for trace volatile analysis, 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 there is concern that the above homogenization would cause trace volatile compounds to be lost, an alternate splitting technique will be used. The undisturbed core or soil will be spooned directly into the two jars by alternating spoonfuls between the sample and the split container. This will ensure a fairly even split while reducing the agitation and exposure of the sample surface area.

5.1.4 Sample Containers and Sample size

Soil samples will be stored in appropriate containers as indicated in the site test plan or as directed by the analytical laboratory. For sample size requirements, refer to the site test plan or discuss with analytical laboratory. Some suggested container types and sample sizes are as follows:

a. Volatile analysis: Glass jar, wide mouth, teflon-faced cap, 125-mL capacity, 100 g sample volume minimum

b. Semi-volatiles: Glass jar, wide mouth, teflon-faced cap, 125-mL capacity, 100 g sample volume minimum

c. Metals: HDPE or glass wide-mouth jar

d. For other soil analysis types including particle-size analysis, nutrient analysis, and moisture determination, samples can be stored in metal, plastic, or glass containers.

5.2 Sample Label and Log

A sample must be labeled with enough information for all parties who may have to deal with it. Refer to the test/project plan for labeling instruction. At a minimum, the samples are to be labeled with the following information:

a. Test Site where sample was collected

b. Soil Boring Number or ID

c. Soil sampling depth

d. Initials of sampler

e. Date and time of collection

f. Information to be recorded in the log/record book, including specific equipment used, sampler, date and time, and any observations about the sampled material or meter readings taken.

5.3 Sample Packing and Shipping

a. The soil samples will be placed in plastic bags and stored in a refrigerator, ice chest, or insulated box on ice immediately after being placed in appropriate containers and labeled. Be sure sample containers and bags are tightly closed and that there is sufficient ice to maintain refrigerated conditions until samples arrive at the laboratory.

b. Control samples and field blanks will not be shipped with contaminated samples.

c. Complete chain-of-custody forms for each cooler. Refer to SOP ENVIR. I-005-00 for proper procedure for completion of chain-of-custody documentation.

d. Ship samples to arrive within 24 hr whenever possible. Shipment will be made by Federal Express (when possible) — Priority Overnight Service with Saturday deliveries specified when applicable.

e. Notify recipient about specifics of shipment.

5.4 Quality Control

a. Descriptions and dates of all of the above activities will be documented in study records.

b. Soil analysis information will be included in the study records. Photographs will be taken periodically and retained with the study records.

c. Records will be kept as indicated in this procedure and will be reviewed periodically by the study/task leader.

Example Procedure

For

In Situ Respiration Testing

1/2. Scope/Purpose

This section describes procedures for conducting an in situ respiration test.

3. References

Hinchee, R.E. and S.K. Ong. 1992. "A Rapid In Situ Respiration Test for Measuring Aerobic Biodegradation Rates of Hydrocarbons in Soil." *Journal of 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.

4. Definitions

Sampling Team: People responsible for conducting the in situ respiration test.

5. Procedure

5.1 Field Instrumentation and Measurement

5.1.1 Oxygen and Carbon Dioxide

Gaseous concentrations of carbon dioxide and oxygen will be analyzed using a GasTech model 3252OX carbon dioxide/oxygen analyzer or equivalent. The battery charge level will be checked to ensure proper operation. The air filters will be checked and, if necessary, cleaned or replaced before the experiment is started. The instrument will be turned on and equilibrated for at least 30 minutes before conducting calibration or obtaining measurements. The sampling pump of the instrument will be checked to ensure that it is functioning. 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.

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

5.1.2 Hydrocarbon Concentration

Petroleum hydrocarbon concentrations will 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 will 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% for the Trace-Techtor™ analyzer to be accurate. When the oxygen drops below 10%, a dilution fitting must be added to provide adequate oxygen for analysis.

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

5.1.3 Helium Monitoring

Helium in the soil gas will be measured with a Marks Helium Detector Model 9821 or equivalent with a minimum sensitivity of 100 ppm (0.01%). 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%), 5,000 ppm (0.5%), and 10,000 ppm (1%).

5.1.4 Temperature Monitoring

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

5.1.5 Airflow Measurement

Before respiration tests are initiated at individual monitoring points, air will be pumped into each monitoring point using a small air compressor as described in Section 5.7. Airflow rates of 1 to 1.5 cfm will be used, and flow will be measured using a Cole-Palmer Variable Area Flowmeter No. N03291-4 (or equivalent). Helium will be introduced into the injected air at a 1% concentration. A helium flow rate of approximately 0.01 to 0.015 cfm (0.6 to 1.0 cfh) will be required to achieve this concentration. A Cole-Palmer Model L-03291-00 flowmeter or equivalent will be used to measure the flow rate of the helium feed stream.

5.2 In Situ Respiration Test Procedures

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

5.2.1 Test Implementation

Air with 1 to 2% helium will 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 will be measured over time. Helium will 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 greater than 10 ft, the required air injection rate may be too high to allow helium injection. The background monitoring point will be used to monitor natural degradation of organic matter in the soil.

Oxygen, carbon dioxide, and total hydrocarbon levels will be measured at the monitoring points before air injection. Normally, air will be injected into the ground for at least 20 hr at rates ranging from 1.0 to 1.7 cfm (60 to 100 cfh). The blowers used will 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 will be 99% or greater purity, which is available from most welding supply stores. The flow rate of helium will be adjusted to 0.6 to 1.0 cfh to obtain about 1% in the final air mixture which will be injected into the contaminated area. Helium in the soil gas will be measured with a Marks Helium Detector Model 9821 (or equivalent) with a minimum sensitivity of 0.01%.

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

At shallow monitoring points, there is a risk of pulling in atmospheric air in the process of purging and sampling. Excessive purging and sampling may result in erroneous readings. There is no benefit in over sampling, and when sampling shallow points, care will be taken to minimize the volume of air extraction. In these cases, a low-flow extraction pump of about 0.03 to 0.07 cfm (2.0 to 4.0 cfh) will be used. Field judgment will be required at each site in determining the sampling frequency.

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

5.2.2 Data Interpretation

Data from the in situ respiration tests will be summarized, and their oxygen utilization rates computed. Details on data interpretation are presented in Section 4.4.

5.3 Quality Control

a. Descriptions and dates of all of the above activities will be documented in study records.

b. Soil analysis information will be included in the study records. Photographs will be taken periodically and retained with the study records.

c. Records will be kept as indicated in this procedure and will be periodically reviewed by the study/task leader.

Example Procedure

For

Soil Gas Permeability Testing

1/2. Scope/Purpose

This section describes procedures for conducting a soil gas permeability test.

3. References

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.

Johnson, P.C., M.W. Kemblowski, and J.D. Colthart. 1990. "Quantitative Analysis for the Cleanup of Hydrocarbon-Contaminated Soils by In-Situ Soil Venting." *Ground Water 28*(3), May-June.

Sellers, K., and C.Y. Fan. 1991. "Soil Vapor Extraction: Air Permeability Testing and Estimation Methods." In: *Proceedings of the 17th RREL Hazardous Waste Research Symposium*, EPA/600/991/002, April.

4. Definitions

Sampling Team: People responsible for conducting the soil gas permeability test.

5. Procedure

5.1 Field Instrumentation and Measurement

5.1.1 Oxygen and Carbon Dioxide

Gaseous concentrations of carbon dioxide and oxygen will be analyzed using a GasTech model 3252OX carbon dioxide/oxygen analyzer or equivalent. The battery charge level will be checked to ensure proper operation. The air filters will be checked and, if necessary, cleaned or replaced before the experiment is started. The instrument will be turned on and equilibrated for at least 30 minutes before conducting calibration or obtaining measurements. The sampling pump of the instrument will be checked to ensure that it is functioning. 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.

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

5.1.2 Hydrocarbon Concentration

Petroleum hydrocarbon concentrations will 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 will 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% for the Trace-Techtor™ analyzer to be accurate. When the oxygen drops below 10%, 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.

5.1.3 Pressure/Vacuum Monitoring

Changes in soil gas pressure during the air permeability test will be measured at monitoring points using Magnehelic™ or equivalent gauges. Tygon™ or equivalent tubing will be used to connect the pressure/vacuum gauge to the quick-disconnect on the top of each monitoring point. Similar gauges will 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 simply switching inlet ports. Gauges are sealed and calibrated at the factory and will be rezeroed before each test. The following pressure ranges (in inches H_2O) will typically be 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 will be measured with a pressure gauge having a minimum range of 0 to 30 psig.

5.1.4 Airflow 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 airflow 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 (~20 scfm in a 2-in. pipe). For lower flow rates, a large rotameter will provide 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 will be corrected to standard temperature and ambient pressure (altitude) conditions.

5.2 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 the soil gas permeability test is initiated, the site will 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 will be sealed to prevent short-circuiting and to ensure the validity of the soil gas permeability test.

5.2.1 System Check

Before proceeding with this test, soil gas samples will 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 will be performed to ensure proper operation of the blower and the pressure and airflow 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 are available for each monitoring point at the onset of the soil gas permeability test. Generally, a 10- to 15-minute period of air extraction or injection will be sufficient to predict the magnitude of the pressure response, and the ability of the blower to influence the test volume.

5.2.2 Soil Gas Permeability Test

After the system check, and when all monitoring point pressures have returned to zero, the soil gas permeability test will begin. Two people will be required during the initial hour of this test — one to read the Magnehelic™ gauges and the other to record pressure (P′) versus time on the data sheet. This will improve the consistency in reading the gauges and will reduce confusion. Typically, the following test sequence will be 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- 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 groundwater 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 will normally be continued until the outermost monitoring point with a pressure reading does not increase by more than 10% over a 1-hour interval.

9. Calculate the values of k and R_I with the data from the completed test; the HyperVentilate™ computer program is recommended for this calculation.

5.2.3 Post-Permeability Test Soil Gas Monitoring

Immediately after the permeability test is completed, soil gas samples will 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% or more, oxygen and carbon dioxide will 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 will provide additional in situ respiration data for the site.

5.3 Quality Control

a. Descriptions and dates of all of the above activities will be documented in study records.

b. Soil analysis information will be included in the study records. Photographs should be taken periodically and retained with the study records.

c. Records will be kept as indicated in this procedure and will be reviewed periodically by the study/task leader.

APPENDIX D

OFF-GAS TREATMENT OPTIONS

APPENDIX D

OFF-GAS TREATMENT OPTIONS

Off-gas treatment is not typically 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 movement of vapors into subsurface structures or air emissions 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 creating an expanded bioreactor. The result is less biodegradation and more volatilization. In general, increasing extraction rates will increase both volatilization and biodegradation rates until the site becomes aerated. At this point, increasing flow rate will not increase biodegradation, but will continue to increase volatilization. The optimal input air flow is the minimum extraction rate that satisfies the oxygen demand. Some volatilization will occur 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 it was possible at the optimal air flow rate to achieve about 85% contaminant removal by biodegradation.

Currently, only 6 of 125 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 been significantly reduced. At Patrick AFB, initial vapor concentrations of total petroleum hydrocarbons (TPH) were as high as 27,000 ppmv. After approximately 75 days of operation, concentrations were reduced to 1,600 ppmv, and the bioventing system was reconfigured for injection. An additional site is the Base Service Station at Vandenberg AFB. Because this site contains high concentrations of the more volatile components of fuels and is an active service station, vapors could migrate into the building on site. 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 then was recirculated through the soil using air injected via biofilter trenches located along the perimeter of the site. Phase II was initiated once TVH concentrations were reduced to <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 section 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 section are derived from information on remedial technologies published by AFCEE (1992 and 1994) and a description of off-gas treatment in a Reference Handbook for soil vapor extraction technology (U.S. EPA, 1991, EPA/540/2-91/003). 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 an internal combustion engine
- 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 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.

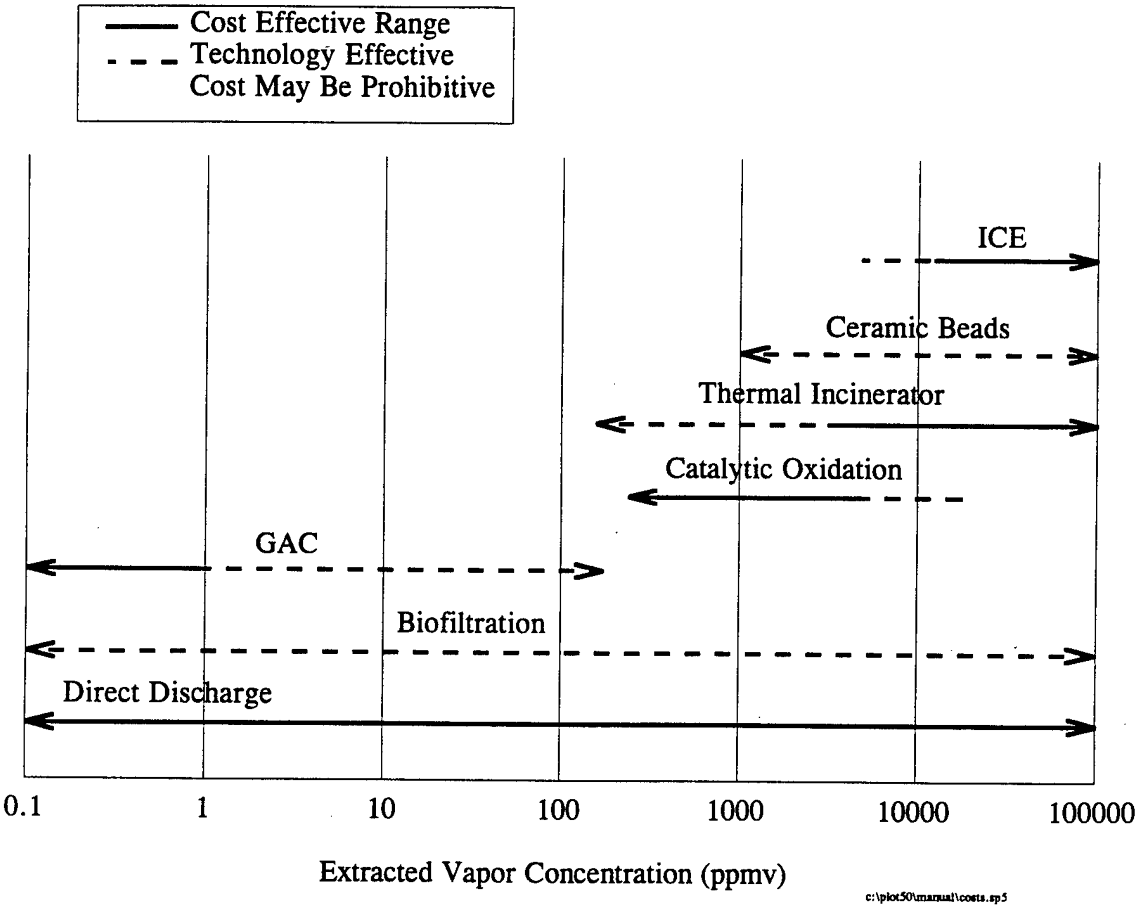

Figure 1. Applicability of Vapor Treatment Options

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 cost sets general ranges of applicability for the 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 usually are 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% of the lower explosive limit (LEL). The ICE units, therefore, gain a significant advantage when the vapor concentration is over 25% of LEL.

Limiting Off-Gas Production

Design and operating features can 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 the 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.

Direct Discharge

Direct discharge involves release of air containing organic vapors directly through a stack. The stack will disperse the vapors but not remove or destroy contaminants. 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 when 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.

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 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, which are needed to determine the design capacity for the reinjection point. The soil volume available 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 is destroying the contaminants rather than increasing contaminant migration. After reinjection is established, surface emission testing may be performed to ensure that 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 buildings are present.

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 to 5,000 ppmv (U.S. EPA, 1994, EPA/542-R-94-003).

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. Up to 90% of the initial

50 ppmv gasoline vapor concentration was removed by the biofilter. These studies also sought to demonstrate the linear relationship between flowrate 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 toluene and gasoline vapor streams. Bench- and pilot-scale reactors were studied.

Adsorption on Carbon or Resin

Adsorption refers to the process whereby molecules collect on and adhere to the surface of an adsorbent solid (U.S. EPA, 1988, EPA/530/UST-88/001). This adsorption is due to chemical and/or physical forces. Physical adsorption (the more common type in this application) is due to Van der Waals' forces, which are common to all matter and result from the motion of electrons. Surface area is the critical factor in the adsorption process because the 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. Because carbon has a complex internal pore structure, activated carbon adsorbents provide a high surface area in a low unit cost material. Commercially available GAC typically has a surface area of 1,000 to 1,400 m^2/gram.

GAC is the most cost effective organic vapor treatment method for a wide range of applications due to its relative ease of implementation and operation, its established performance history in commercial applications, its ability to be regenerated for repeated use, and its applicability to a wide range of contaminants at a wide range of flow rates. Many vendors sell or lease prefabricated, skid-mounted units that can be put into operation with a few days notice. However, carbon adsorption is economical only for lower mass removal rates. When the vapor concentration is high, carbon replacement or regeneration may be prohibitively expensive.

On-site regeneration of the carbon is an alternative to carbon replacement with off-site disposal or reactivation. Such systems regenerate the carbon in place, using steam or hot gas to desorb the contaminants. The contaminants recovered in liquid form then can 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, PA), Carbtrol Corporation (Westport, CT), and Nucon (Columbus, OH) among many others, supply adsorption isotherms and pressure drop curves for the various 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 to 2,000 lb of activated carbon that may accommodate flow rates from below 400 standard cubic feet per minute (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). Therefore, the cost of activated carbon treatment can be roughly estimated as being about $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% can be processed with little reduction on the adsorption efficiency for organic contaminants. The resin adsorbents as amenable to regeneration on site. Skid mounted modules are available consisting of two resin adsorbent beds. The design allows one bed to be online treating off-gas while the other bed is being regenerated. During the desorption cycle, all of the 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).

Catalytic Oxidation

Catalytic oxidation is an incineration process that uses catalysts to increase the oxidation rate of organic contaminants, yielding equivalent destruction efficiency at a lower temperature than for 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 required for the oxidation reaction. Increased concentration and reduced activation energy increase the rate of organics oxidation (Kiang, 1988). Figure 2 shows a schematic diagram of a catalytic incinerator unit.

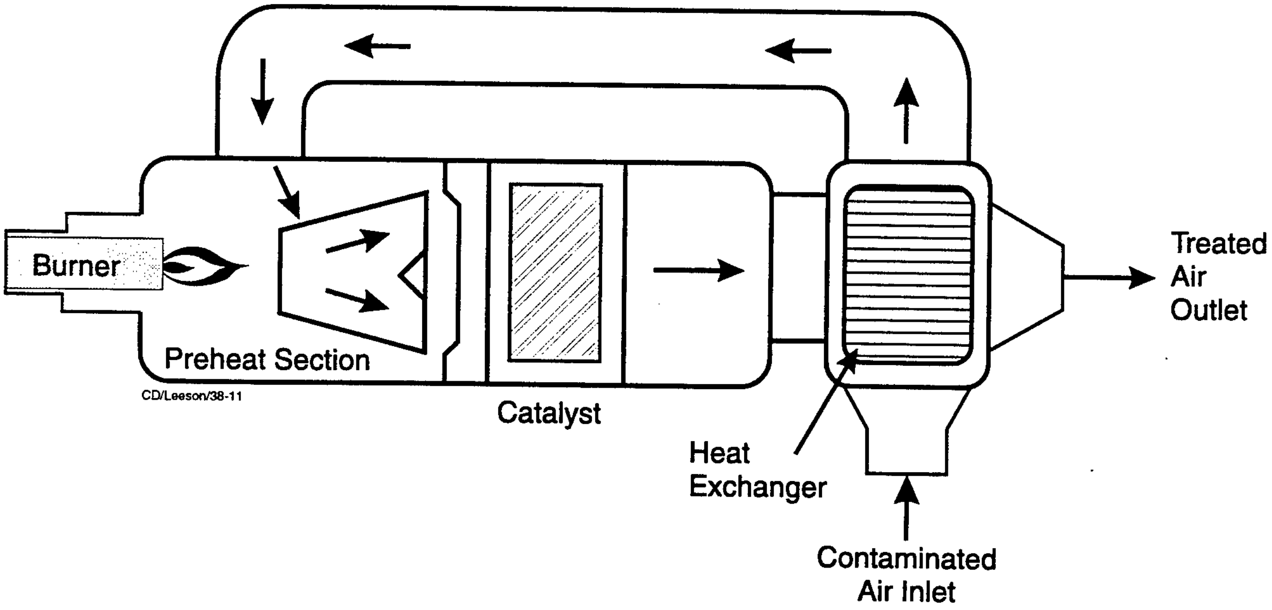

Figure 2. Schematic Diagram of Catalytic Oxidation

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

The metal catalyst and support are exposed to the heated off-gas in a catalytic oxidation unit. The catalytic oxidation unit will use either a fixed bed or 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, EPA/625/6-86/014).

The main advantage of catalytic oxidation versus thermal incineration is the much lower temperature required with a catalyst. These systems typically operate at 600 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 a 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 also is a concern with these units, as with any incineration method. The maximum permissible total hydrocarbon concentration varies by site but usually is below 25% of the LEL. The total hydrocarbon concentration in the vapor is measured continuously 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 will deactivate the catalyst by 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 for treatment of chlorinated compounds. New technologies potentially capable of treating chlorinated compounds by catalytic oxidation currently are under development and are beginning to appear 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 in the approximate range of $40,000 to $60,000 (in 1991 dollars) (AFCEE, 1992). Operations, maintenance, and monitoring costs will be site-specific. Makeup fuel will be required if the hydrocarbon concentration falls below the level necessary to maintain the required temperature. At the Hill Air Force Base 914 site (Smith et al., 1991), the extracted hydrocarbon concentration was approximately 600 ppmv and flow rate 1,500 cfm. To maintain the minimum temperature, an average of 1,500 gallons of propane was used every month at an average cost of $2,000 per month. All thermal oxidation processes will require makeup fuel to treat low concentration wastestreams, and the makeup fuel generally will be proportional to the operating temperature. Some fuel may be saved by heat recuperation.

Flame Incineration

Flame incineration uses high-temperature, direct-flame combustion to produce rapid oxidation of organic contaminants. Flame incinerators for treating organic vapors in off-gas are typically single-chamber, refractory-lined units containing an open burner. Flame incinerators often are equipped with heat exchangers, where hot combustion gases leaving the incinerator preheat the incoming off-gas stream. Heat recovered from the combustion gas improves thermal efficiency and reduces fuel costs. When operated with adequate temperature and residence time, flame incineration treatment will oxidize hydrocarbon contaminants to carbon dioxide and water. For most contaminants, acceptable contaminant destruction efficiency is achieved with an operating temperature in the range of 1,400 to 1,600 °F and a residence time of 1 second (AFCEE, 1992). Addition of makeup fuel is usually needed to maintain the temperature required to ensure adequate mineralization. Natural gas or propane typically serves as the supplemental fuel. The destruction of the contaminants is a major advantage of this technique over carbon adsorption, which only concentrates the contaminants onto the carbon, which must then be regenerated or disposed.

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% of the LEL (AFCEE, 1992). The LEL for gasoline is between 12,000 ppmv and 15,000 ppm, depending on the gasoline's grade (Little, 1987).

Direct incineration is not appropriate for influent vapor streams that contain chlorinated compounds. Complete combustion of these compounds will generate 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. However, due to the higher operating temperature, fuel use will be higher in a flame incinerator. When the flammable contaminant vapor concentration is sufficiently high, the heating value from oxidation of the contaminant reduces fuel use so at higher hydrocarbon concentrations flame incineration may be less costly than catalytic incineration. At lower vapor concentrations, the cost of makeup fuel will be much greater than for catalytic incineration, and the overall cost will probably be 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 to 5,000 ppmv (AFCEE, 1992).

Internal Combustion Engines

Internal combustion engine treatment accomplishes destruction of organic contaminants by 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 follows:

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

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-cubic-inch-displacement 4-cylinder engine running at 2,250 rpm and 10 inches Hg engine vacuum with an atmospheric pressure of 30 inches of mercury would have an off-gas treatment capacity of 52 scfm. ICE treatment units are available in sizes from 140 cubic inches to 460 cubic inches. Currently available ICE treatment units operate the engine at 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 to 75%.

The engines are 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, EPA/540/2-91/003). 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 the end of 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. A range suggested by one equipment vendor was 750 hours 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 auto 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 among 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, CA) 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% (U.S. EPA, 1991, EPA/540/2-91/003, p. 93). ICEs are especially useful for treating vapor streams with high concentrations of TPH (up to 30% volume) to levels below 50 ppm. Tests of benzene, toluene, ethylbenzene, and xylenes (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 can be expressed as mass removal rate. One ICE operator reported a mass removal and destruction rate of over 1 ton per day (about 12 gph).

ICE off-gas treatment units are able to handle high concentrations of organic contaminants in the extracted air. As discussed above, incineration units, (e.g., catalytic oxidation units and flame incinerators) usually are limited to inlet vapor concentrations of 25% of the LEL. Because the inlet concentration for an ICE unit can be in the combustible range, 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% of the LEL. Inlet vapor concentration as high as 300,000 ppmv have been reported (U.S. EPA, 1991, EPA/540/2-91/003). 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 to 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.

ICEs as vapor treatment devices for extracted soil vapors offer 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% 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 the air flow capacity (see equation above). As a result, the ICE usually is 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 ease of 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 on-site monitoring.

Noise associated with the operation of the engine could be a concern near residential areas or occupied buildings. Noise can be abated by adjusting engine speed during certain time 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 certainly in the same general range as for 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 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.

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 oxidation. A vapor stream passes through the packed bed that thermally destroys the contaminants. The packing geometry combined with uniform high temperature of the ceramic beads is reported to give good 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 1800°F. No additional energy input is required if the heat value of the vapors is sufficient. This point is near a concentration of 2000 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 technology currently is investigating its applicability to the remediation market (U.S. EPA, 1991, EPA/540/2-91/003).

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+%, 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 still would be produced.

In the photocatalytic oxidation process, volatile organic compounds are converted to carbon dioxide and water by exposure to ultraviolet (UV) light. When chlorinated organics are present, hydrogen chloride gas and/or chlorine also are 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 to 99% 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, EPA/542-R-94-003).

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