REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
May 2004

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
3/03-3/04

4. TITLE AND SUBTITLE (Do not use all capital letters)
Procedures for Conducting Bioventing Pilot Tests and Long-Term Monitoring of Bioventing Systems

5a. CONTRACT NUMBER
F41624-03-D-8613

5b. GRANT NUMBER
NA

5c. PROGRAM ELEMENT NUMBER
NA

5d. PROJECT NUMBER
743375

5e. TASK NUMBER
TO 19

5f. WORK UNIT NUMBER
NA

6. AUTHOR(S)
Mr. Doug Downey, Dr. Ross Miller, Mr. Tom Dragoo

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Parsons
1700 Broadway, Suite 900
Denver, Colorado 80290

8. PERFORMING ORGANIZATION REPORT NUMBER
N/A

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Center for Environmental Excellence
Brooks Air Force Base
San Antonio, Texas

10. SPONSOR/MONITOR'S ACRONYM(S)
AFCEE

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NA

12. DISTRIBUTION / AVAILABILITY STATEMENT
A- Unlimited Distribution

13. SUPPLEMENTARY NOTES

14. ABSTRACT (200 word max)

This document provides a summary of soil bioventing procedures with an emphasis on pilot testing and the long-term monitoring of full-scale bioventing systems. The document is intended for use by engineers and scientists who are responsible for planning or conducting soil remediation projects using in situ bioventing methods. The document is an updated version of earlier AFCEE bioventing protocols.

15. SUBJECT TERMS Bioventing, Soil Remediation, In-Situ Remediation, Soil Vapor Extraction

16. SECURITY CLASSIFICATION OF:
UNCLASSIFIED

a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Mr Jerry Hansen
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	None	80	**19b. TELEPHONE NUMBER** *(include area code)* (210) 536-4353

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

FINAL

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U.S. AIR FORCE

Prepared For

Air Force Center for Environmental Excellence
Brooks Air Force Base
San Antonio, Texas

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1700 Broadway, Suite 900
Denver, Colorado 80290

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PROCEDURES FOR CONDUCTING BIOVENTING PILOT TESTS AND LONG-TERM MONITORING OF BIOVENTING SYSTEMS

Prepared for

THE AIR FORCE CENTER FOR ENVIRONMENTAL EXCELLENCE
BROOKS AIR FORCE BASE
SAN ANTONIO, TEXAS

May 2004

Prepared by

PARSONS
1700 Broadway, Suite 900
Denver, Colorado 80290

This document was prepared under AFCEE Contract F41624-03-D-8613, Task Order 0019. This document replaces AFCEE's 1992 Test Plan and Technical Protocol For A Field Treatability Test for Bioventing (Hinchee et al, 1992), and provides environmental engineers and scientists with an updated approach for conducting bioventing pilot tests and for monitoring the long-term progress of bioventing systems. The following individuals have made significant contributions to the science and application of the bioventing technology that directly supported this document: Mr. Doug Downey, Mr. Tom Dragoo, Mr. Marty Faile, Mr. Patrick Haas, Mr. John Hall, Mr. Jerry Hansen, Dr. Robert Hinchee, Mr. Jim Gonzales, Dr. Andrea Leeson, Dr. Ross Miller, Mr. John Ratz, and Mr. Sam Taffinder.

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SECTION 1

INTRODUCTION TO BIOVENTING

1.1 BIOVENTING FUNDAMENTALS

Bioventing is the process of aerating soils to add oxygen and to stimulate biodegradation of a wide range of hydrocarbons. Bioventing differs from soil vapor extraction (SVE) in that bioventing is generally accomplished through the injection of air into the subsurface while SVE relies on the removal of the volatile compounds via soil vapor extraction. SVE systems are operated to maximize the volatilization of low molecular weight compounds while bioventing systems are operated to maximize the in-situ biodegradation of all hydrocarbons while minimizing volatile migration or emissions. Mechanically, these systems are similar. Bioventing requires less air movement and smaller blowers. SVE requires larger blowers, and often requires moisture removal (a knockout drum) to protect the blower, and a vapor treatment system to remove volatile compounds before emitting soil gas to the atmosphere. Figure 1.1 shows a typical bioventing system compared to a typical SVE system.

Bioventing is best suited for petroleum hydrocarbons with greater than 8 carbon atoms (C8+) such as jet fuels, diesels and heating oils. SVE is best suited for chlorinated solvents such as perchloroethene (that are not aerobically degraded) or fresh gasoline spills that have a high concentration of benzene and other molecules with less than 8 carbon atoms (-C8). Bioventing has been successfully used at gasoline sites, however, special precautions must be taken to minimize vapor migration. Figure 1.2 illustrates the physical properties of hydrocarbons and the applicability of bioventing and SVE. Additional details on specific compound biodegradability are found in Volume 1 (page 59) of the Bioventing Principals and Practices Manual. It is important to point out that even when SVE is used for gasoline site remediation, a significant amount of biodegradation takes place in the subsurface as oxygen rich soil gas is moved through the gasoline contaminated soil.

1.2 BIOVENTING BACKGROUND

During the 1970s and 1980s, in-situ bioremediation of hydrocarbon contaminated soil focused on the use of water as the primary conveyor of oxygen to the subsurface. The use of hydrogen peroxide to supply higher concentrations of oxygen was the most frequently applied method. Independent research completed by the U.S Air Force at Eglin AFB (Spain and Downey, 1988; Hinchee et al. 1989) concluded that hydrogen peroxide was unstable and resulted in poor oxygen distribution. In addition to peroxide stability problems, it is very difficult to deliver large quantities of water through contaminated soil. It is difficult to deliver large quantities of oxygen in water due to limited oxygen solubility (even with amendments like peroxide). For these reasons, the

FIGURE 1.1

BIOVENTING AND SVE CONCEPTS

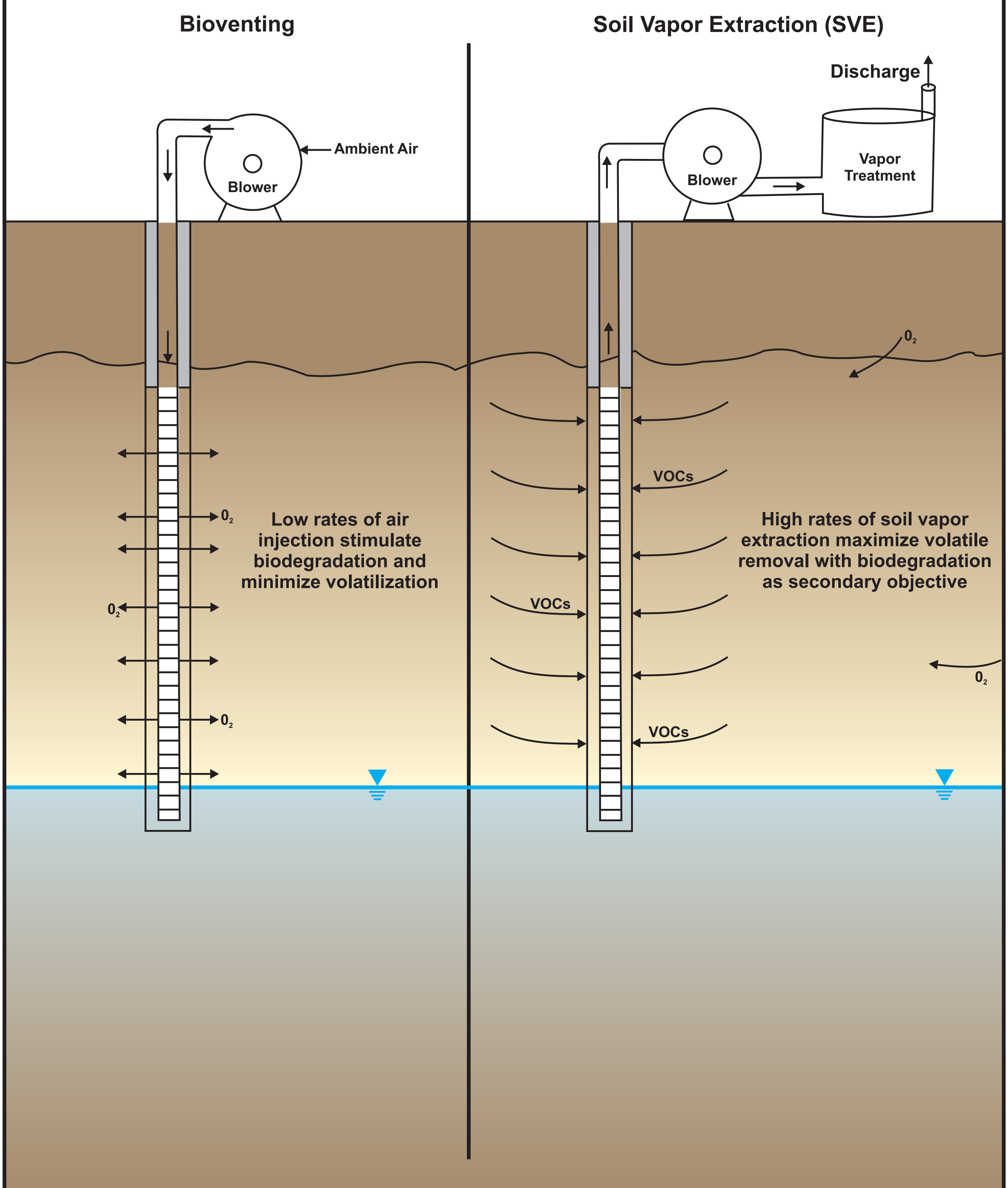

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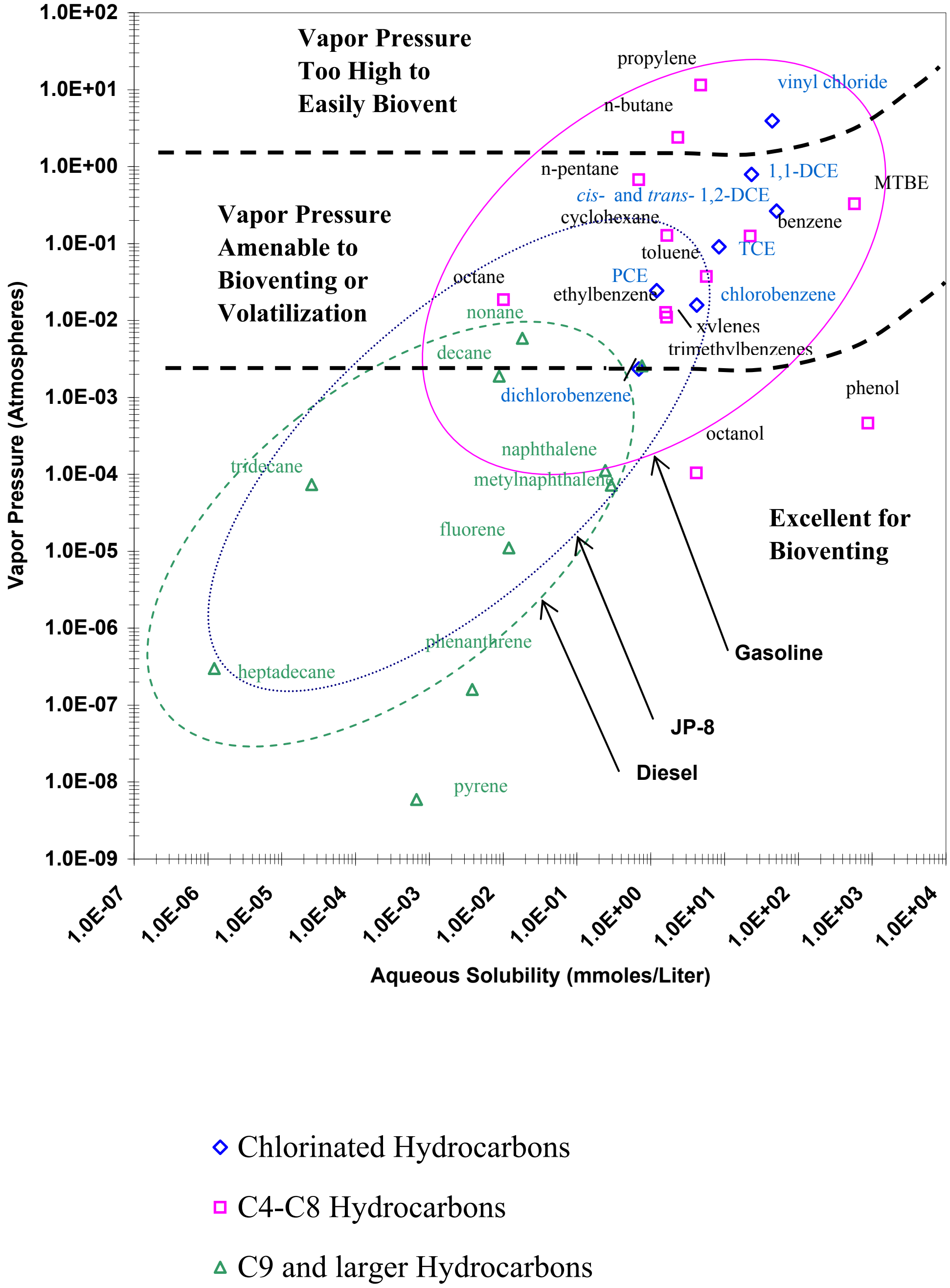
FIGURE 1.2
Relationship Between Contaminant Physicochemical Properties and Potential for Bioventing



use of air to convey oxygen has had much greater success in a variety of soil types and site conditions.

To the authors' knowledge, the first documented evidence of biodegradation resulting from air injection was reported by the Texas Research Institute in a 1980 study for the American Petroleum Institute. The first field scale demonstration of bioventing was completed by Jack van Eyk for Shell research in 1982 (van Eyk and Vreeken, 1986). Beginning in 1988, the US Air Force began bioventing research at Hill AFB, UT. Additional USAF studies at Tyndall AFB, FL (Miller, 1990) and Eielson AFB, AK led to the development of a methodology for pilot testing and measuring rates of biodegradation. A more complete discussion of early bioventing history and development is found in the document *Principles and Practice of Bioventing Volume 1: Bioventing Principles* (Leeson and Hinchee, 1995) found on the AFCEE website.

In 1992, AFCEE published the initial version of the *Test Plan and Technical Protocol For A Field Treatability Test for Bioventing* (Hinchee et al, 1992). This document was written to provide a standardized method of bioventing testing and was based on the limited bioventing experience of the Air Force and others at a handful of test sites. In 1992, the AFCEE Technology Transfer Division initiated a 145-site bioventing pilot test initiative using the 1992 Protocol as a generic test plan. In order to provide a wide range of test conditions, test sites were selected at 56 Air Force installations located in 38 states, including Hawaii and Alaska. Following initial soil and soil gas sampling, and initial pilot testing, small bioventing systems were installed on test sites and were operated for a period of one year. A summary of the results of this comprehensive pilot study are found in the document *Bioventing Performance and Cost Results From Multiple Air Force Sites* (Downey and Miller, 1996) which is also posted on the AFCEE website.

1.3 LESSONS LEARNED FROM AIR FORCE NATIONWIDE PILOT TESTING

The 145-site bioventing pilot test initiative provided a conclusive demonstration of the widespread applicability and success of this technology. The key results of this multi-site test are summarized below:

- Initial bioventing tests were successful at 142 of the 145 test locations. At two sites, excessive soil moisture and clay soils made it impossible to inject air and supply oxygen. At one site in the desert, biodegradation rates were too low for bioventing to be the primary site remedy. This result demonstrates that natural bacteria are present to support petroleum biodegradation in all soils with the exception of very low moisture soils (<2% moisture by weight). **Lesson Learned:** Wherever air could be injected into the soil, over 99 percent of the sites had significant biodegradation rates.

- Air injection was the preferred method of oxygen supply. Vapor extraction was used at five gasoline-contaminated sites to reduce the potential for uncontrolled vapor migration. After several months of vapor extraction to reduce accumulated vapors, these systems were converted to air injection systems. **Lesson Learned:** Highly volatile mixtures such as gasoline may require an initial 3 to 6 month period of SVE before converting the system to bioventing. If vapor treatment is required, rent the vapor treatment equipment for a few months, do not buy it.

- Bioventing was successfully applied at sites contaminated with a variety of petroleum products including JP-4, JP-8, gasoline, diesel, waste oils, Stoddard® solvent and hydraulic fluids. **Lesson Learned:** Bioventing degrades a wide variety of petroleum hydrocarbons.

- The average initial biodegradation rate was 1,200 milligrams of hydrocarbon per kilogram of soil per year. Rates of biodegradation decreased over time as the most biodegradable compounds were consumed leaving the less bioavailable compounds to degrade at a slower rate. **Lesson Learned:** Rates of biodegradation are slower for longer chain hydrocarbons and compounds such as polyaromatic hydrocarbons (PAHs). Natural levels of nitrogen and phosphorus were sufficient to sustain biodegradation. No nutrients were added.

- Based on soil sampling before and after one year of bioventing, the average total petroleum hydrocarbon (TPH) concentration was reduced 24 percent. The average benzene, toluene, ethylbenzene, xylenes (BTEX) reduction was 97 percent in the first year. **Lesson Learned:** Bioventing is very effective at rapidly reducing more water soluble and bioavailable compounds such as benzene. These are also the most mobile and toxic compounds, so bioventing can rapidly reduce chemical risks. Bioventing is well-suited for sites with cleanup standards based on BTEX rather than TPH.

- Successful bioventing tests were completed in extreme climates including Alaska and California deserts. **Lesson Learned:** Higher biodegradation rates were generally measured in warmer soils but some biological activity was measured in soils at $1^{?}$ C to $5^{?}$C.

- The cost of bioventing ranged from $10 to $60 per cubic yard. These simple systems were operational 95% of the available time and only a few of the pilot units required blower repairs. **Lesson Learned:** On small sites, the pilot system and monitoring points can often be converted into a full-scale system for little additional cost. Bioventing is cost effective, particularly for larger sites with deep or inaccessible contamination (beneath concrete or buildings). Bioventing is reliable because it is mechanically simple. Figure 1.3 illustrates the basic unit cost of bioventing for different soil volumes. Please note cost assumptions.

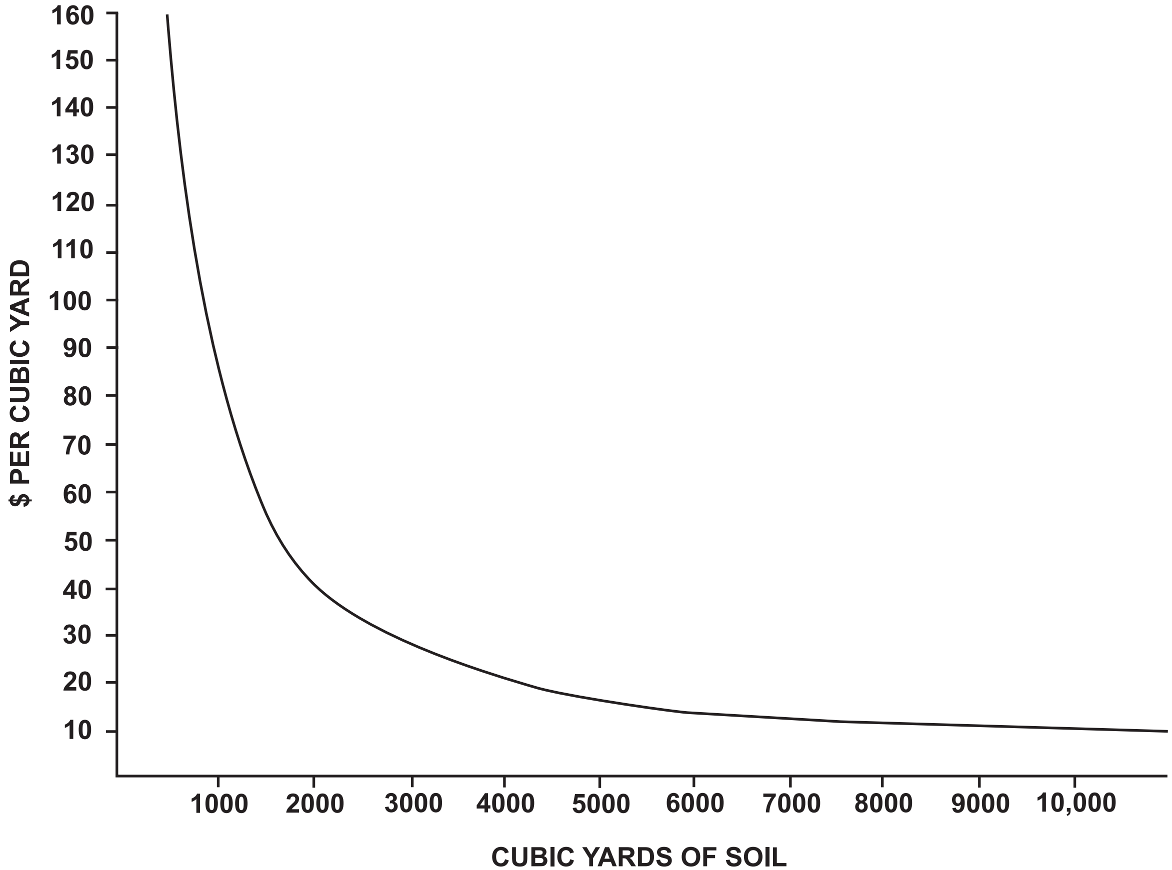
1.4 OVERVIEW OF FIELD PILOT TESTING

As discussed in Section 1.2, the probability of bioventing being successful at petroleum hydrocarbon sites is very high. Although biodegradation will almost always occur when air (oxygen) is injected into the soil, there are benefits derived from conducting a pilot test. Pilot tests have three primary objectives that are discussed in this section.

1. Pilot testing will determine if the contaminated soil volume is anaerobic and in need of oxygen to stimulate biodegradation.

FIGURE 1.3

BIOVENTING UNIT COSTS



Cost Includes: Pilot Test, Full-Scale Installation, Two Years of Operation, Annual Respiration Testing/Reporting.

Does Not Include: Power Hookup Cost, Concrete or Asphalt Trenching/Repair, Regulatory Negotiations, Final Soil Sampling.

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2. Pilot testing will determine if the contaminated soil volume has adequate permeability to promote uniform oxygen distribution via air injection.

3. Pilot testing will confirm that the soil contains petroleum degrading microorganisms and establish the initial rates of biodegradation that can be expected for the site.

1.4.1 Determining Baseline Oxygen Conditions

Initial soil gas surveys using temporary soil gas probes can be helpful in determining the areas of highest soil contamination and indicate if a site is naturally aerated. Soil gas oxygen and carbon dioxide are measured using handheld detectors that are described in Section 3. The absence of oxygen in soil gas is a good indicator of microbial degradation of hydrocarbons. In general, the lower the oxygen levels in the soil gas the more biologically active (and contaminated) the soil volume is. Soil gas oxygen and carbon dioxide levels can provide a valuable insight into where the most and least contaminated soils occur on a site.

In most soils, the natural aeration of the soils caused by barometric pressure change is insufficient to supply oxygen more than a foot or two into the soil. Generally, the rate of oxygen uptake by microbes is greater than the natural aeration rates. In fact, only two of the 145 pilot test sites were determined to be naturally aerated or "passively biovented." These sites both had shallow contamination (< 6 feet), and very sandy soils that allowed natural aeration to at least 5 percent oxygen levels. Appendix A describes soil gas screening methods that can be used to determine baseline soil gas oxygen conditions.

> *NOTE: Proper sampling methods and calibrated equipment for oxygen monitoring are critical to produce meaningful and successful bioventing pilot tests. Care must be taken to ensure that sampling trains are not leaking atmospheric air. These precautions are discussed in Section 4.*

1.4.2 Air Permeability and Oxygen Distribution

Once the contaminated soil volume is identified, and the absence of oxygen has been confirmed through soil gas sampling, the practitioner must determine if the contaminated soil volume has adequate permeability to allow uniform oxygen distribution via air injection. Air injection testing is accomplished by using a small blower with an injection rate that is generally less than 50 standard cubic feet per minute (scfm). Air can be injected into an existing groundwater monitoring well (if properly constructed and located) or a new bioventing vent well that is specifically designed for air injection. There are several types of blowers that will work for bioventing applications, each with a particular range of pressure and flow to match the expected soil permeability characteristics of the site. Section 3 describes how to select a blower for different site conditions and how to construct a bioventing injection well.

Following vent well installation and baseline soil gas sampling, air is injected into the soil and the distribution of oxygen in the soil is measured at several vapor monitoring points (MPs) located at varying depths and distances from the air injection vent well.

Section 3 provides details on the typical air injection test layout. As air is injected, the increase in soil gas pressure and changes in percent oxygen are measured at each MP. In a successful pilot test, oxygen increases of at least 2 percent should be measured in all MPs. Since low flow rates are used, and oxygen is being consumed by microbes, it may take several days for the oxygen to infiltrate to the most distant MPs. This test provides valuable information for determining an air injection flow rate that will deliver oxygen within a known radius of influence. Section 4 describes air injection test procedures in more detail.

1.4.3 Estimating Biodegradation Rates

The final segment of the bioventing pilot test is the estimation of biodegradation rates using an in-situ respiration test. When soil microbes degrade petroleum hydrocarbons they consume a predictable quantity of oxygen and produce carbon dioxide. This process is known as microbial respiration. During microbial respiration, approximately 3.5 pounds of oxygen are consumed for every one pound of hydrocarbon degraded to carbon dioxide. Because changes in soil gas oxygen levels can be easily and reliably measured, oxygen utilization is the primary method for estimating the rate of hydrocarbon biodegradation in the soil.

An in-situ respiration test is accomplished by injecting air (oxygen) into the contaminated soil mass and then measuring the uptake of oxygen in the soil gas over time. This is the equivalent of a biological oxygen demand (BOD) test for biodegradation in soils. Oxygen can be added during the air permeability and oxygen influence test described above, or air can be injected into individual MPs using a small, one-scfm air pump. Regardless of the method of air injection, an initial oxygen concentration of 10-15 percent is desired to start the test. Once this concentration of oxygen is achieved, the blower or air pump is turned off and the soil gas is periodically sampled and analyzed over a 1 to 3 day period to determine the rate of oxygen uptake. This test confirms that bacteria are present to degrade the hydrocarbons and provides the key data to estimate the initial hydrocarbon degradation rate. Section 4 describes in-situ respiration test procedures and calculations in more detail.

1.5 OVERVIEW OF DOCUMENT

This document is organized into five sections including this introduction. Section 2 describes how to select and layout a bioventing test site. Section 3 shows how to establish test wells and describes the basic test equipment you will need. Section 4 describes bioventing test procedures and Section 5 describes how to monitor a full-scale bioventing system.

SECTION 2

TEST SITE SELECTION AND PLANNING

This section provides simple steps for screening sites for bioventing applications. A flowchart is provided to help you determine if bioventing is the right technology for a specific candidate site. A review of site data is required, and an initial soil gas survey can be useful in completing the test plan.

2.1 SITE SCREENING

Despite its widespread success, bioventing is not appropriate technology for all petroleum spill sites. At some sites it would be a poor use of time and money to conduct a bioventing pilot test. Figure 2.1 provides a flowchart to help you determine if a bioventing pilot test is appropriate for a specific candidate site. Note that some sites may be too small to justify bioventing if they can be excavated and soil disposed of for less than the cost of setting up and operating a bioventing system.

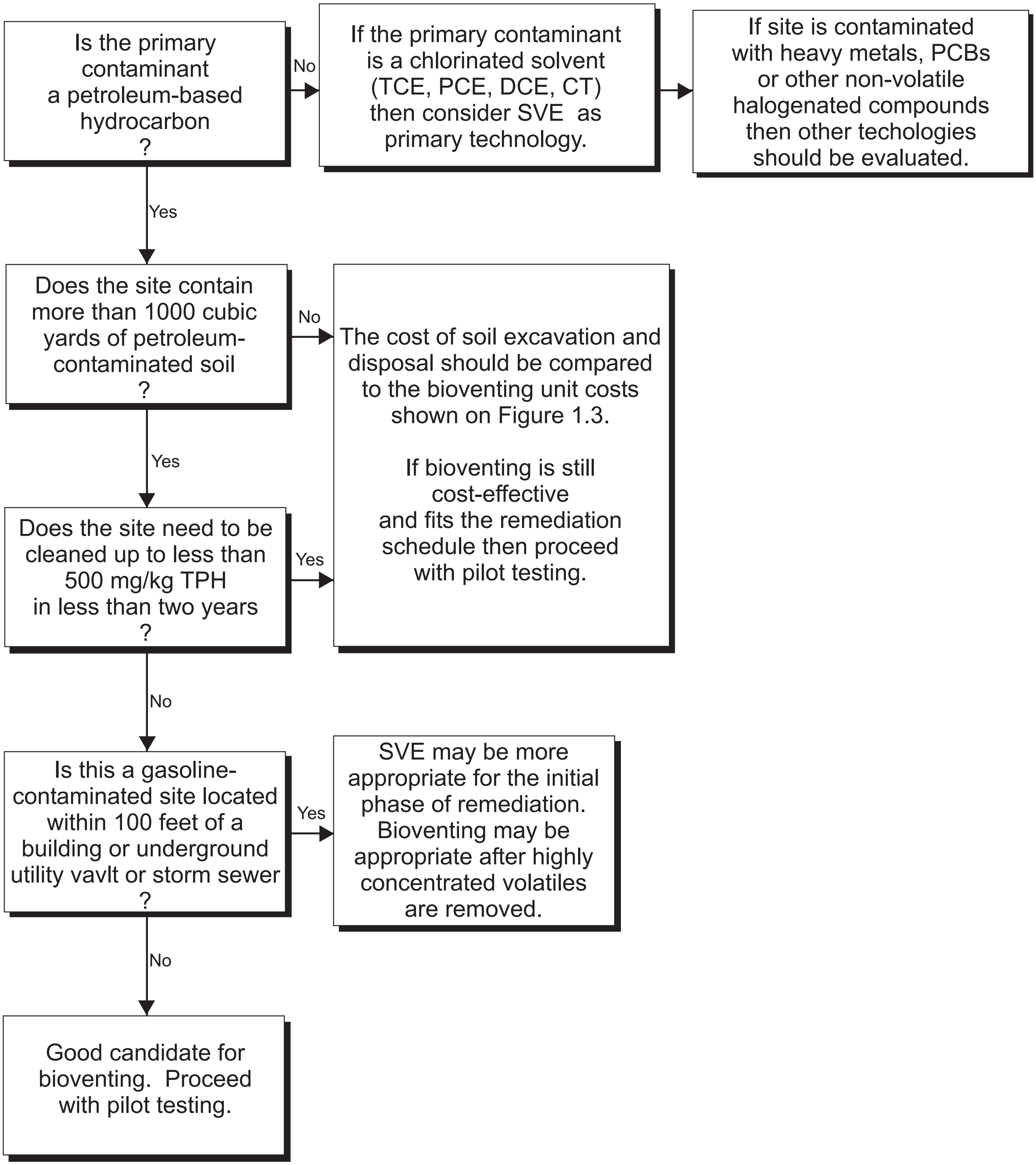
2.2 SITE DATA REVIEW

If the site meets the basic criteria specified in Figure 2.1, a more detailed review and collection of site data will assist in the test plan preparation. The following information is needed to plan a bioventing pilot test.

- Name and contact information for the Air Force project manager.
- Name and contact information for the facility manager or person responsible for the physical site.
- Name and contact information for regulatory person with oversight responsibilities.
- A brief history of the site and the source of contamination.
- A site map showing existing soil contamination levels, locations, and depths.
- A description of site geology and hydrogeology. A cross-section showing site geology and the water table in relation to soil contamination is very helpful.
- The location of all monitoring wells on the site and well completion diagrams including the screened intervals.
- The location of the nearest power supply - preferably a 120/240V breaker box with at least 30 amps of open capacity.

FIGURE 2.1

BIOVENTING SITE SCREENING



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- Utility maps showing all underground and overhead utilities at the site.
- Surface features such as buildings, concrete or asphalt thicknesses, stormwater drainage patterns.

The majority of this information should be available from previous site characterization reports or gathered during a site walk. The Air Force project manager should assist the remediation consultant in obtaining a copy of these reports (electronic copies are most useful), and provide guidance on the level of regulatory interface that is required for the pilot testing activities.

2.3 INITIAL SOIL GAS SURVEYS (OPTIONAL)

Although an initial soil gas survey is optional, there are some sites where this data can be very valuable in pilot test planning. Sites with limited characterization of soil contamination or sites contaminated with gasoline, may require additional information that can be quickly gained from a soil gas survey. Soil gas data can be collected in one day and then incorporated directly into the pilot test plan and site layout. Soil gas data can assist in determining the center of contamination, where the air injection vent well(s) should be located, and the approximate area where a lack of oxygen may be limiting biodegradation. Experience has shown that 5+ percent of soil gas oxygen is adequate to support continued biodegradation, and represents an easily measured, minimum oxygen target for both site assessment and bioventing design.

At gasoline sites, soil gas surveys can also be used to measure initial levels of hydrocarbon vapors and to determine if SVE is needed to control explosive vapor migration or benzene migration. As a rule, sites with soil gas containing more than 4,000 parts per million by volume (ppmv) of total hydrocarbon vapor, or more than 1 ppmv of benzene vapor, should be carefully evaluated. If buildings, storm sewers or utility vaults are within 100 feet of high vapor levels, SVE should be considered for initial soil treatment. The selection of SVE or bioventing will depend on many factors that should be evaluated by a remediation professional.

Appendix A provides additional guidance on how to conduct soil gas surveys for the purpose of determining bioventing applications and design.

2.4 DEVELOPING A TEST PLAN

A simple bioventing test plan is useful for communicating and coordinating test activities, responsibilities, and schedules among several key individuals and agencies.

The remediation consultant generally develops the test plan, however, the client (Air Force POC) may prepare a portion of the test plan as a part of the contract statement of work. The test plan represents an agreement on where, how, and when testing will be completed and should provide all parties with a clear understanding of their responsibilities. Appendix B provides a test plan outline that has been successfully used at hundreds of bioventing pilot test sites and is a suggested starting point for your test plan.

2.5 REGULATORY PARTICIPATION

Most regulatory agencies welcome pilot testing activities and view them as a positive step toward site cleanup. The Air Force has gained approval for bioventing pilot tests at virtually all major installation in the United States and in all 10 EPA regions. In most cases, testing can be completed without formal regulatory review of test plans, but each base should determine its own policy regarding regulatory participation.

SECTION 3

TEST WELLS AND EQUIPMENT

This section describes the test wells and equipment that are required to conduct a bioventing pilot test. Site-specific flexibility will be required and the test well design will vary based on available wells or specific design requirements specified by local or state regulatory agencies. The designs provided in this section represent the minimum recommended specifications for a successful pilot test. In some states, even vent wells may require a construction permit. Check local regulatory requirements.

Field notes should be maintained during construction describing all vent well and vapor MP details. Deviations from standard design should be noted. Figure 3.1 illustrates a typical bioventing test layout which includes a single air injection vent well and three vapor monitoring locations that have multiple sampling depths. As discussed below, it may be possible to use existing groundwater monitoring wells to collect some of the soil vapor data.

3.1 VENT WELLS

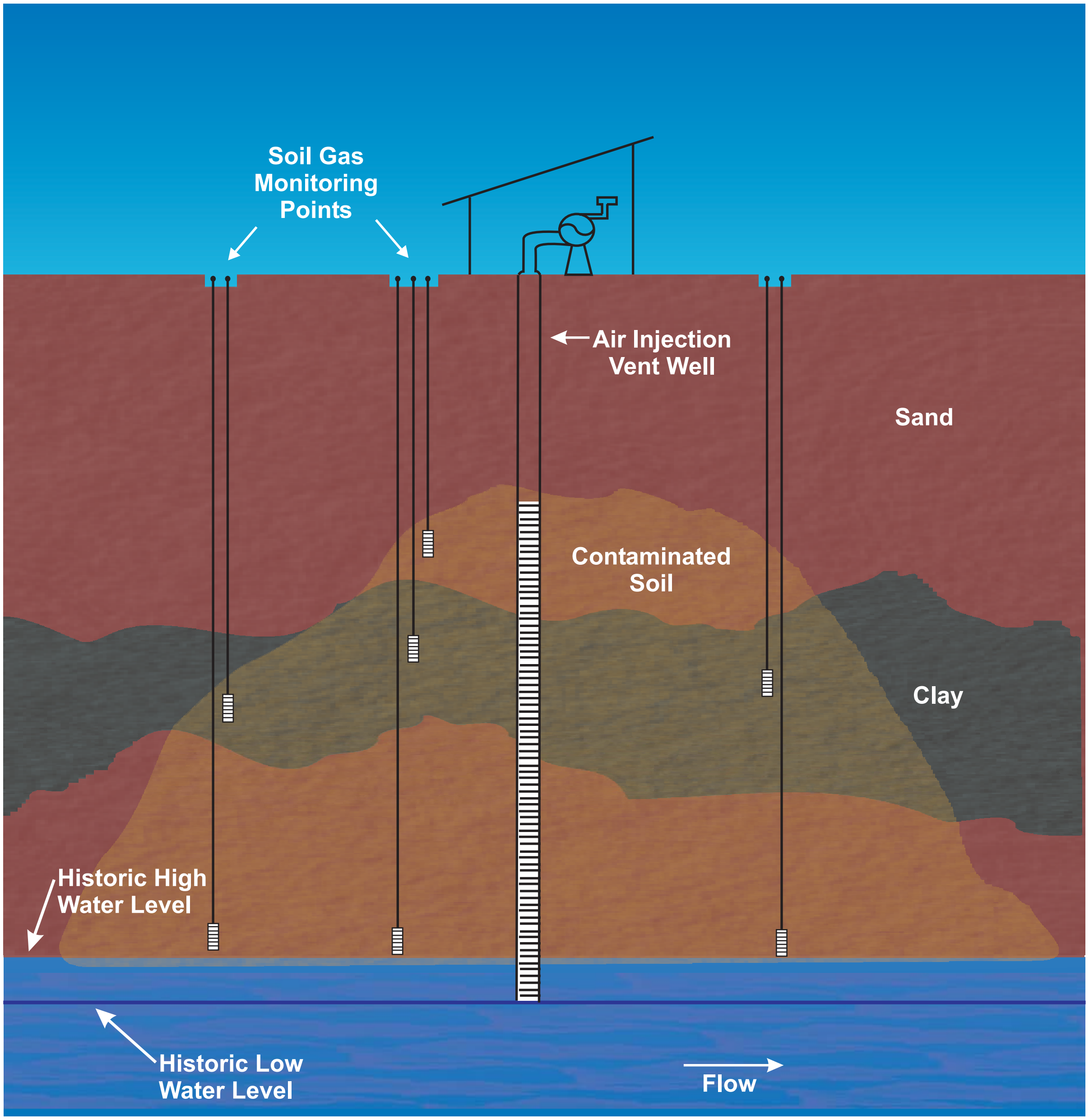
A vent well and blower system will be established to provide airflow through the subsurface, creating a pressure gradient for distributing air (oxygen) in a radius of influence around the vent well and increasing subsurface oxygen levels for in-situ respiration testing. The location and construction of the vent well will follow these general criteria:

- The vent well will be sited as near to the center of the spill area as possible. If soil contamination is poorly defined, a soil gas survey can assist in locating the center of contaminant mass (Appendix A). This location will ensure that data gathered from the test will be representative of full-scale conditions and will increase the chance of providing oxygen to the entire contaminated soil volume. On many small sites, the vent well used during the pilot test can be converted into the primary vent well for full-scale remediation.

- Figure 3.2 illustrates a typical vent well design. The diameter of the vent well may vary between 2 and 4 inches. On most sites, a 2-inch vent will provide adequate airflow for pilot testing. For sites with contamination extending below 30 feet, or sites with low permeability silt and clay soils, a 4-inch vent well is recommended to provide additional air injection capacity. Groundwater monitoring wells that are screened several feet above the current water table can also be converted into temporary vent wells. Well construction information should be reviewed before using an existing groundwater well. This option is particularly appropriate for

FIGURE 3.1

BASIC BIOVENTING DESIGN



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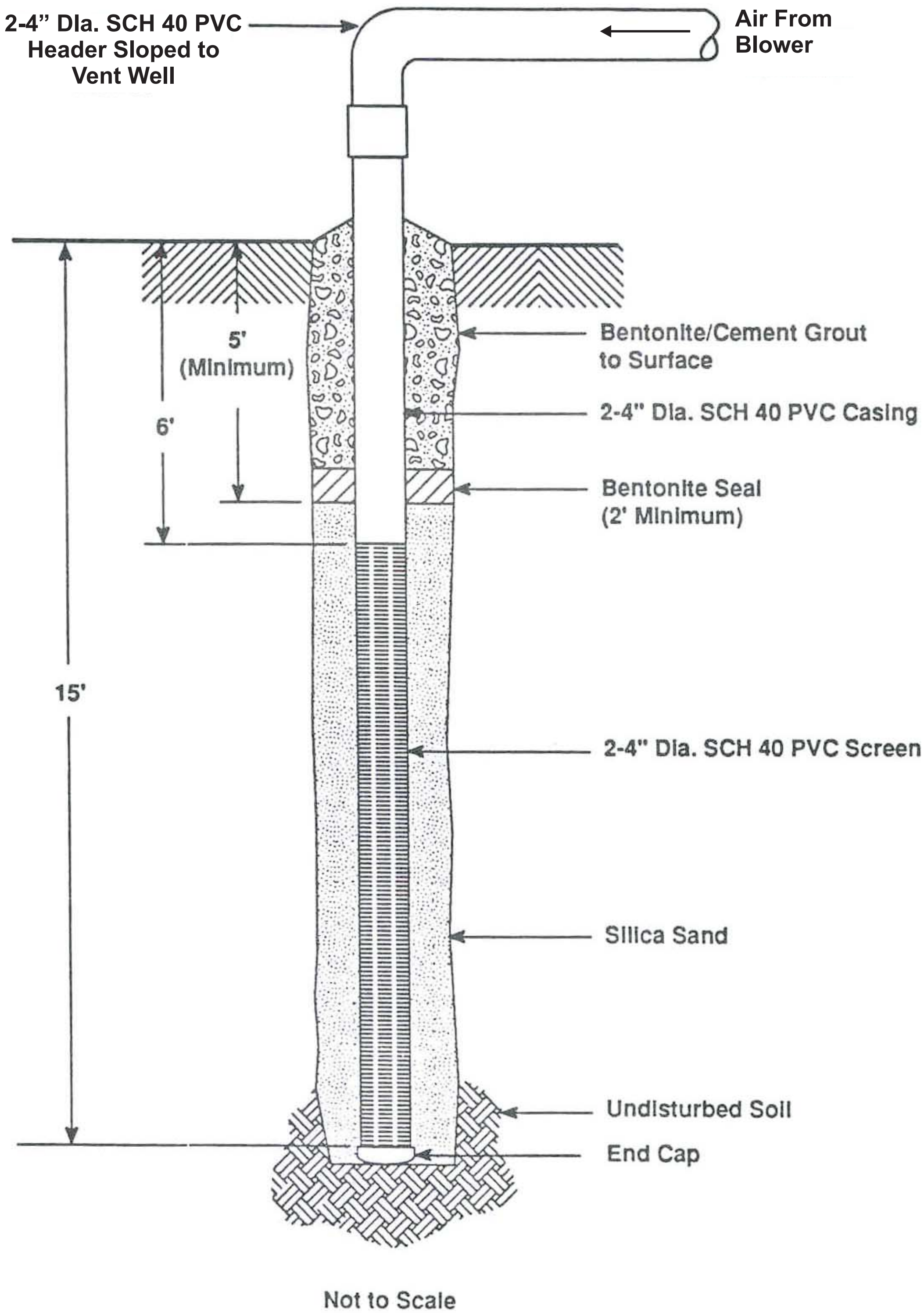

FIGURE 3.2

TYPICAL INJECTION
VENT WELL CONSTRUCTION

draw\743375 Schematic Diagram.cdr scan pg6 ma 1-27-04

sandy sites with contamination that is concentrated near the water table. Sandy soils allow a larger quantity of air to be injected in a small screened interval.

- The vent well will normally be constructed of Schedule 40 polyvinyl chloride (PVC), and screened with a slot size of 0.04-inch or greater to minimize pressure loss through the screen and maximize airflow through the soil. All connections must be air tight. If threaded pipe is used it should be sealed with Teflon® tape or each joint sealed by an o-ring. The use of PVC glue is also permissible for air injection systems. The screened interval should extend through as much of the contaminated profile as possible, with the bottom of the screen set to the historic low water level at the site. The top of the screened interval should be at least 5 feet below grade to prevent short-circuiting of air to the surface. If there is significant contamination in the upper 5 feet of the soil, a shallower screen depth can be attempted if care is taken to install an air tight seal between the screen and the surface. Horizontal vent wells have been successfully used at sandy sites with shallow contamination. All types of shallow wells will require a fully-cured, bentonite or cement grout in the annular space between the screen and the surface.

> ***NOTE:*** *Most short-circuiting occurs in low permeability soils where air is forced up the annular space "blowing out" the seal and ruining the well. Seals that are still wet and not solidified are much more likely to blow out. Seals can also shrink in dry climates, leading to short circuiting of injected air. Seal integrity should be inspected regularly.*

- Hollow-stem augering is the recommended drilling method for vent wells; however, a solid-stem auger is also acceptable in more cohesive soils. Whenever possible, the diameter of the annular space will be at least two times greater than the vent well outside diameter. The annular space corresponding to the screened interval will be filled with silica sand or equivalent.

- Sites with the majority of the soil contamination in the capillary fringe may benefit from a vent well that is designed with a shorter screened interval that will focus air into the capillary fringe. These wells may have several feet of screen below the water table to take advantage of seasonal water level changes. During high water seasons, these wells may actually function as sparging wells. Sparging will introduce oxygen to the capillary fringe more effectively than a vent well screen constructed above the capillary fringe.

3.2 SOIL GAS MONITORING POINTS

Soil gas monitoring points will be used for pressure and soil gas measurements and should be installed at a minimum of three locations. Multiple screened depth intervals may be required at each monitoring point location. Figures 3.1 and 3.3 illustrate the recommended placement and design for soil vapor monitoring points (multi-depth version). Soil gas monitoring points should be located in the most contaminated area of the site to provide meaningful in-situ respiration test results. It may not be possible to

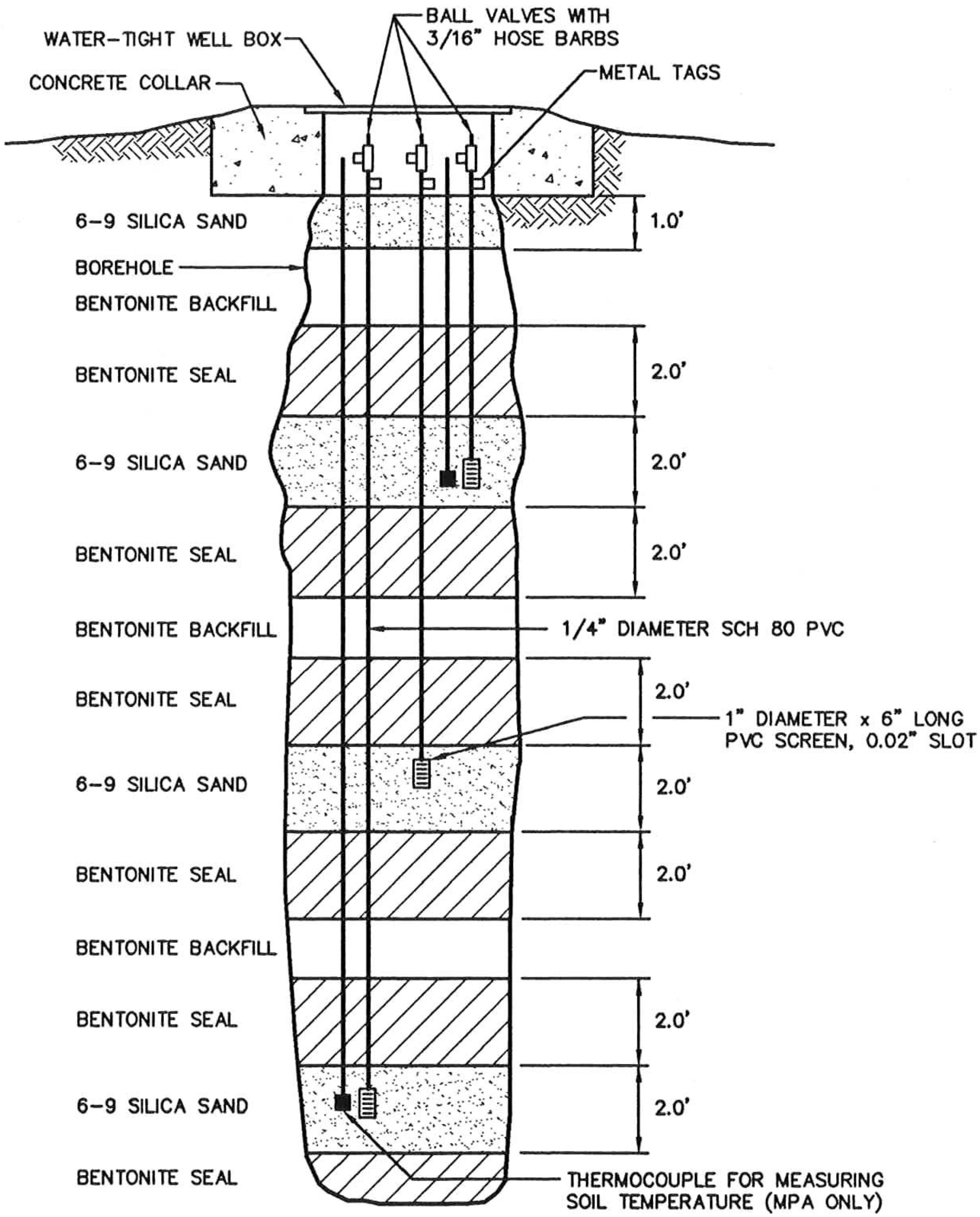

FIGURE 3.3

TYPICAL MONITORING POINT CONSTRUCTION DETAIL

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locate all monitoring points in contaminated soil, especially the points furthest from the vent well. It is critical to ensure that the point closest to the vent well be located in contaminated soil and if possible, the intermediate point should be in contaminated soils. Although thermocouples are shown on Figure 3.3, they should be considered optional and included only if a specific use for the data is identified. In general, they will not be necessary.

3.2.1 Location of Monitoring Points

A minimum of three monitoring points is recommended; ideally these will be in a straight line and at the intervals recommended in Table 3-1. At sites without underground obstructions (tank pits, utilities, concrete walls), three monitoring locations are generally appropriate. Additional monitoring point locations may be necessary for a variety of site-specific reasons including underground obstructions or soil variations. A monitoring point should always be located between the vent well and any basements or utility corridors that may be at risk from vapor migration. This is particularly important for gasoline- contaminated sites or JP-4 sites containing free product.

TABLE 3-1
RECOMMENDED SPACING FOR MONITORING POINTS

Soil Type	Max Depth of Contaminated Soil (ft)	Spacing Intervals (feet from vent well)
Coarse Sand	5	5-15-30
	15(1)	10-20-50
	>15	20-40-80
Medium Sand	5	5-15-30
	15(1)	10-20-40
	>15	20-40-80
Fine Sand	5	5-15-30
	15(1)	10-20-40
	>15	20-40-80
Silts	5	5-15-30
	15(1)	10-20-30
	>15	10-30-50
Clays	5	5-10-25
	15(1)	10-20-30
	>15	10-20-40

(1) Assuming 10 ft of vent well screen, if more screen is used, the > 15-ft spacing will be used.

(2) Note that monitoring point intervals are based on a venting flow rate range of 1 cfm/ft screened interval for clays to 3 cfm/ft screened interval for coarse sands.

3.2.2 Depth of Monitoring Points

The number of depth intervals monitored at each location will depend on the total depth of the contamination and the variation in soil types (permeability). As a rule of thumb, one sampling interval per 10 feet of contaminated depth is sufficient. For sites over 30 feet deep, this interval can be increased. The deepest screen should be placed at the bottom of soil contamination if a water table is not encountered. If groundwater is encountered, and the capillary fringe is contaminated, a sampling point should be located at the depth of the seasonal high water level. This point may be flooded during high water conditions but will provide valuable data on bioventing in the capillary fringe during lower water table conditions. For sites with very shallow contamination, screens can be completed as shallow as 3 feet below land surface.

If both sandy and silt/clay soils are contaminated, it is important to locate a proportionate number of screened intervals in each soil type as shown in Figure 3.1. It is important to determine if air injection is providing oxygen to low permeability silt/clay soils.

> ***NOTE:*** *Practice has shown that oxygen will diffuse into low permeability soils over time even though initial testing may not show oxygen influence in these soils.*

3.2.3 Construction of Monitoring Points

Most state and local regulatory agencies do not regulate unsaturated zone soil gas monitoring point construction. Monitoring point construction will vary depending on the soil type, depth of drilling, and the drilling technique. The recommended design for auger drilling is shown in Figure 3.3. Each monitoring interval includes a 6 to 12-inch section of 1-inch diameter slotted screen with a bottom cap and a top coupling that reduces to ¼-inch. The short screened section is centered in the sand pack for each monitoring interval. The screen is connected to a ¼-inch I.D. riser tube made of rigid Schedule 80 PVC (or equivalent). In low-permeability or wet soils, a longer screened interval and sand pack may be desirable to increase air flow. A bentonite seal that is approximately 2-feet thick is recommended to separate monitoring intervals.

For relatively shallow installations, and in more permeable soils, a hydraulic push system such as Geoprobe® can be used to install vapor monitoring points. The same basic design should be used except that ½-inch diameter screened PVC should be used to ease the installation of each soil gas point inside of the probe rod annular space. The probe manufacturer normally has an established procedure that should be used for soil vapor point installation. For bioventing installations it is critical that the annular space above the screened interval be sealed with bentonite. GeoInsight® has developed a casing with an expanding annular seal that can provide an air-tight seal in direct push holes. A separate push hole will be required for each screened depth interval if a hydraulic push system is used.

Hand driven soil gas collection systems are also available for shallow sites (<10 feet). In some systems, a sacrificial drive point with TygonTM, TeflonTM, or other appropriate tubing is driven to the desired depth. The outer steel drive tube is then retrieved, leaving the drive point and the inner flexible tubing in place. Because this type of installation allows for no sand pack or seal, hand-driven points should only be used in sandy, non-cohesive soils that will close in around the sample point and tubing to prevent short-circuiting.

NOTE: *Do not use hand driven points in cohesive silt or clay soils due to the high likelihood of air leaks down the drive hole.*

A flush-mounted, water tight well box should be used for the surface completion of auger, hydraulic push or hand-driven points. Tubing from each monitoring point should be finished with an air-tight ball valve and a 3/16-inch hose barb. Each monitoring point tube must be carefully labeled during construction to avoid mixing up depth intervals. The tubing should be labeled with a firmly attached metal tag or directly by engraving or in waterproof ink. The following labeling technique is recommended:

[Code for Site] -[Code for Monitoring Point} -[Depth to Center of Screened Interval]

For example, the 25-foot monitoring interval at Monitoring Point B (MPB) on Site FT02 would be labeled: FT02-MPB-25.

3.2.4 Optional Thermocouples

On sites located in cold regions, thermocouples should be installed to monitor the soil temperature at various depths. Thermocouples are optional for all other sites. The thermocouples should be installed at several depths but only in monitoring point closest to the vent well. Thermocouples used are either J or K type. The thermocouple wires will be labeled using the same system as for the tubings.

3.3 COLLECTION OF SOIL SAMPLES

Soil samples should be collected from the borings prepared for the vent well and monitoring points. Soil samples will generally be collected from a split-spoon sampler. As each boring on the site is advanced, a boring log should be prepared to describe the soils and evidence of contamination encountered at one-foot depth intervals. By recording the soil type and evidence of contamination (staining/odor) the optimum depth of screened intervals can be determined. A minimum of four soil samples should be collected from the most contaminated portion of the site. This will generally include the vent well boring and the inner most vapor monitoring point boring. If funds are available for more samples, one sample should be collected from the depth corresponding to each MP screened interval. There should be at least two representative samples of each contaminated soil type. Each soil sample should be analyzed for the following chemical and physical characteristics:

- TPH (Could include TEPH, TVPH, or a TPH fractionization method) depending on state requirements)
- BTEX (For gasoline and jet fuel spills)
- PAHs (If required for diesel and heating/heavy oils)

- Sieve analysis (For estimating soil bulk density)
- Moisture content (For estimating biodegradation rates, air permeability)

For the sieve analysis and moisture analysis enough soil should be collected to fill a 500-milliliter large mouth plastic or polyethylene container. The container should be sealed to prevent moisture loss and then placed in a cooler for shipment. Special procedures for preserving these samples will not be required, as only physical properties of the soil will be analyzed.

Samples for TPH and BTEX analysis must be collected, contained, and shipped in a manner that will prevent volatilization losses. Sampling methods for TPH and BTEX are generally described in base-wide sampling and analysis plans or other references.

Each soil sample should be labeled to identify the site, boring location and depth, and time of collection. Chain-of-custody forms will accompany each shipment to the laboratory. In addition to the chain-of-custody forms, each sample will be logged into the project record book along with a complete description of where and how it was collected.

3.4 TEST EQUIPMENT

3.4.1 Blower Systems

The type and size of blower used in a bioventing pilot test will be determined based upon the site specific soil type, the thickness of the contaminated interval and factors such as available power. In an attempt to minimize the blower unit types in the Air Force bioventing inventory, and to standardize piping and instrumentation, two typical blowers are specified:

3.4.1.1 Blower One

Application: Contaminated interval in sandy soils or predominantly sand soils with thin (< 5 feet) silt or clay layers.

- Typical Specifications:
  - explosion-proof regenerative blower
  - 15 to 80 scfm at 50 to 10 inches of H_2O pressure respectively
  - 1-HP explosion-proof motor
  - single-phase, 230V power source

3.4.1.2 Blower Two

Application: Soils that are predominantly silt and clay soils or fine sandy soils with moisture contents greater than 20 percent by weight.

- Typical Specifications:
  - explosion-proof positive displacement, pneumatic, or rotary vane blower – 20 to 60 scfm at 200 to 60 inches of H_2O respectively
  - 3 to 5-HP explosion-proof motor

– single-phase, 230V power source.

Test blowers can be mounted on a small skid or portable cart with mounting brackets and pipe fittings to create the basic blower systems shown in Figure 3.4. Explosion-proof blowers and motors are recommended for use on a variety of test sites because they can be used for SVE applications or on fuel storage facilities where explosion-proof equipment is mandatory.

3.4.2 Blower Accessories and Instrumentation

Figure 3.4 and Figure 3.5 illustrate the basic blower accessories and instrumentation package. Inlet air filters are recommended to prevent particles from damaging the blower. The collection of pressure and flow information is critical to the bioventing full-scale design. A vacuum gauge is located between the air filter and the blower to ensure the filter is not impeding air flow to the blower. A temperature gauge is located immediately downstream of the blower to measure outlet temperatures that normally rise 50° to 100° F through the blower. Due to the temperature rise, steel piping is recommended at the outlet side of the blower. PVC piping will melt, particularly when higher injection pressures are required. Steel piping is also recommended for sites where the air supply line must be left on the ground surface. PVC is easily damaged and can fail under high pressure conditions.

A manual flow control valve is located immediately downstream of the blower to allow unneeded flow to be released before the air enters the well. Note that this valve is always placed on a tee off the primary flow pipe. An automatic pressure relief valve is located on a tee downstream of the blower.

> ***NOTE:*** *The relief valve should be set to release air whenever the pressure exceeds 90 percent of the manufacturer's maximum pressure rating for the blower. This will protect the blower motor from burning out if wet soil conditions or a rising water table are preventing air flow into the ground.*

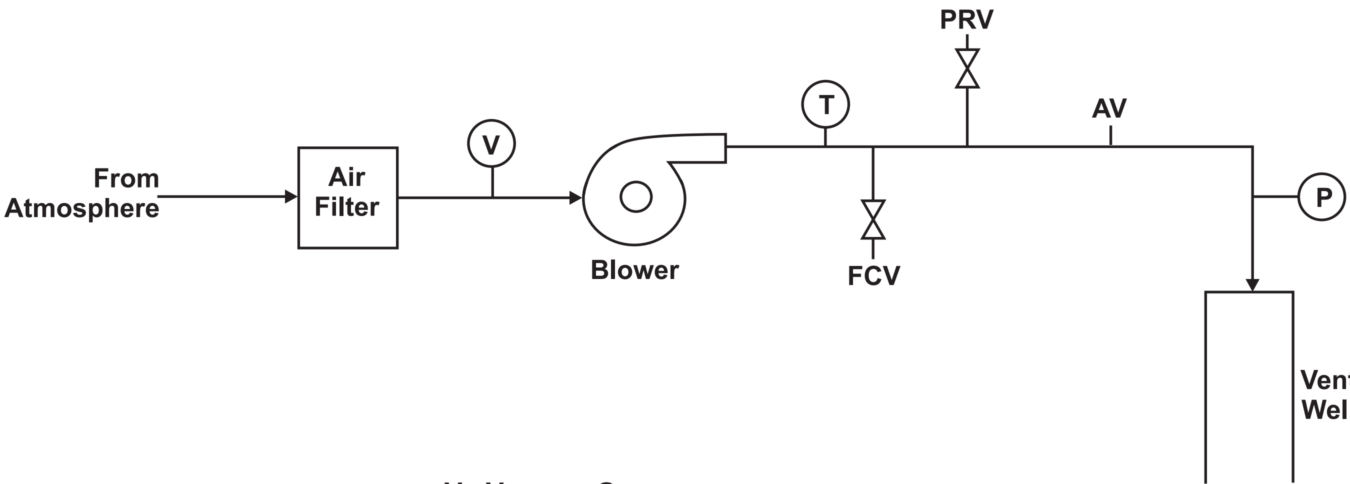
Air flow in bioventing systems can best be measured using a hand-held thermal anemometer probe that is inserted into a ¼ to 3/8-inch hole in the air injection pipe. A 2-inch I.D. pipe or larger is recommended for all flow measuring devices and the probe should be inserted at least 18 inches from any valve or bend in the piping. Flow meter manufactures provide charts for adjusting air flow based on temperature and altitude. Pitot tubes, orifice plates and rotometers are not recommended for measuring air injection flows.

Flow can also be estimated from blower performance curves if the entire air stream is being injected into the vent well if both the flow control valve and pressure relief valves are closed. This method is recommended when a relatively new blower is being used but is less reliable for blowers with over 1000 hours of use.

> ***NOTE:*** *If the manufacturer's blower curve is used, the total pressure across the blower equals the sum of the upstream vacuum gauge and downstream pressure gauge.*

FIGURE 3.4

BIOVENTING SYSTEM INSTRUMENTATION FOR AIR INJECTION



V - Vacuum Gauge

P - Pressure Gauge

T - Temperature Gauge

FCV - Flow Control Valve

PRV - Pressure Relief Valve

AV - Air Velocity Measurement Port
(plugged when not in use)

draw\743375 Blower System.cdr ma 1/28/04

FIGURE 3.5

TYPICAL REGENERATIVE BLOWER SYSTEM

draw\743375 Photos.cdr pg1 ma 02-26-04

3.5 SOIL GAS MONITORING INSTRUMENTS

3.5.1 Soil Gas Purge Pumps

Soil gas monitoring points must be purged before a representative soil gas sample can be collected. Small, electric air pumps are used to both purge and collect soil gas samples from permanent and temporary soil gas points. The most suitable pumps for bioventing applications are either oil-less rotary vane or diaphragm pumps capable of moving 0.5 to 1.5 cfm at vacuums as high as 270 inches H_2O. Air pumps that operate off a 12-V car battery are available for remote site sampling. High-volume peristaltic pumps are another option for sites with low permeability soils.

3.5.2 Oxygen and Carbon Dioxide

Soil gas concentrations of oxygen are at the heart of any successful bioventing pilot test. As such, the use of a reliable and properly calibrated oxygen and carbon dioxide detector can not be over emphasized. Appendix C provides a summary of several detectors that are commercially available. The Air Force is not endorsing any particular detector and recommends that the bioventing test engineer review the latest line of instruments before purchasing or renting a detector. Many of these detectors require up to 30 minutes of warm up to equilibrate before conducting calibration or obtaining measurements. The manufactures warm up and calibration procedure should be strictly adhered to.

Detectors should be calibrated each day prior to use. At a minimum, the oxygen detector should be calibrated using atmospheric oxygen (air at 20.9%) and a zero percent oxygen standard that must be purchased from a calibration gas company. The zero percent oxygen standard is particularly critical to successful soil gas sampling at bioventing sites. The carbon dioxide detector is generally contained within the same hand held instrument as the oxygen detector. The carbon dioxide detector is calibrated using atmospheric carbon dioxide (<0.05 %) to "zero" the detector and a 10 percent carbon dioxide standard to check higher levels expected in contaminated soils. Calibration gases can be purchased from a specialty gas supplier and are often made available through instrument rental firms.

> ***NOTE**: The most efficient gas standard is one that contains zero % oxygen and 10 % carbon dioxide in 90 % nitrogen mix. This single gas standard can be used to calibrate both detectors.*

To calibrate the instrument with standard gases, a three-liter Tedlar® bag 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 to allow flow into the instrument (most instruments have their own air sampling pump that draws air through the detector). The instrument is then calibrated against the standard gas according to the manufacturer's instructions. Figure 3.6 shows a detector in the calibration mode. The instrument is then calibrated against atmospheric concentrations. If recalibration is required, the above steps are repeated.

FIGURE 3.6

O_2/CO_2 DETECTOR
IN CALIBRATION MODE

3.5.3 Volatile Hydrocarbon Detectors

Volatile petroleum hydrocarbon concentrations are screened in the field using a handheld hydrocarbon detector. Appendix C lists several types of detectors that are particularly suited for jet fuel and gasoline vapors. These instruments use a platinum-based catalyst detector and most are equipped with 100 ppmv, 1,000 ppmv, and 10,000 ppmv range settings to improve accuracy over a variety of concentrations. If gasoline or JP-4 free product is found at the test site, the detector should be calibrated using a 4,000 ppmv hexane standard. If JP-8 or heavier diesels/heating oils are present, a 500 ppmv hexane standard is more appropriate. If available, Mylar® bags are recommended for holding hexane calibration gases during the calibration process to minimize sorption to the bag.

When hydrocarbon concentrations are below 100 ppmv, a flame ionization detector (FID) provides good accuracy. A photoionization detector (PID) is *not* acceptable for detecting fuel hydrocarbons. PIDs are appropriate for low levels of chlorinated solvents.

> ***NOTE**: Extracting air directly with direct reading instrumentation should be avoided as these instruments are not designed to pull a vacuum or calibrated against a vacuum. Direct reading instrumentation will generally use a side stream of air (at atmospheric pressure) discharged from a vacuum pump.*

3.5.4 Air-Tight Chamber

One of the challenges of bioventing tests is the prevention of atmospheric oxygen leaks into the soil gas sample. This is particularly true when soil gas is extracted from low-permeability soils at higher vacuums. A standard 12-inch diameter vacuum desiccator can be modified to collect soil gas samples in a manner that minimizes the potential for air leaks. Section 4.1.2 and Figure 4.2 provide additional details on how to modify and use the desiccator for collection of soil gas samples.

3.5.5 Temperature Monitoring

For arctic sites, in-situ soil temperature can be monitored using Omega Type J or K thermo-couples (or equivalent). The thermocouples can be connected to an Omega OM-400 Thermo-couple Thermometer (or equivalent). Each thermocouple should be calibrated in ice water before field installation.

3.5.6 Pressure/Vacuum Monitoring

Changes in soil gas pressure during the air injection testing will be measured at monitoring points using Magnehelic® or equivalent high-quality gauges. Tygon® or equivalent tubing can be used to connect the hand-held pressure/vacuum gauge to the hose barb on the top of each monitoring point. A valve and hose barb can also be installed at the top of the vent well to check injection pressure at the vent 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 should be re-zeroed before each test. The following pressure ranges (inches H_2O) should be available for bioventing pilot tests:

- Sandy Soils: 0-0.5”, 0-1", 0-5", 0-10" , 0-20", 0-100" ranges
- Silt/Clay Soils: all of the above plus 0-200" range

3.5.7 Airflow

Airflow measurements will be important for the air injection/permeability test and for measuring air flow into the soil over time. Thermal anemometers are recommended for measuring the 10-50 scfm flows used for air injection pilot vent wells. The manufacturer’s directions should be used for installing and calibrating these devices. All flow rates should be corrected to standard temperature and ambient pressure (altitude) conditions using the manufacturer’s conversion charts. A flow sampling port should be provided for each vent well if multiple vent wells are used.

SECTION 4

TEST PROCEDURES AND DATA ANALYSIS

This section describes basic bioventing pilot test procedures and how to evaluate the test data for use in full-scale system designs. A bioventing pilot test can be broken down into a three step process:

1. Determine baseline concentrations of oxygen, carbon dioxide and volatile hydrocarbons.

2. Use the blower system to inject air into the central vent well and determine how far and fast oxygen moves into the surrounding soil and estimate a radius of pressure and oxygen influence.

3. Turn off the air supply and use MP soil gas measurements to estimate the rate of oxygen uptake in the soil gas (in-situ respiration rate).

4.1 MEASURING BASELINE SOIL GAS CONDITIONS

On most petroleum contaminated sites, the general location of subsurface contaminants has been characterized before the bioventing pilot test. If the distribution of contamination is unknown, a soil gas survey is recommended to identify areas of high contamination, the extent of contamination, and areas that are oxygen deficient. Appendix A provides additional details on conducting an initial soil gas survey. This section will describe the procedures for collecting baseline soil gas samples from the soil gas monitoring points that have been established for the pilot test.

4.1.1 Monitoring Point Purging

Prior to collecting a soil gas sample for analysis, the MP must be purged of atmospheric air. Figure 4.1 shows the equipment set up for MP purging. The following purging procedure is recommended:

1. Check out your purge pump to make sure it is operating without being connected to any tubing. Calibrate your O_2/CO_2 and TVH detectors following procedures in Section 3.4.2 and 3.4.3.

2. Connect Tygon® tubing to the hose barb at the top of the MP and to the vacuum end of the purge pump (hose barbs can be screwed into the treads at the inlet and exit of the purge pump.) Open the air-tight valve at the top of the MP.

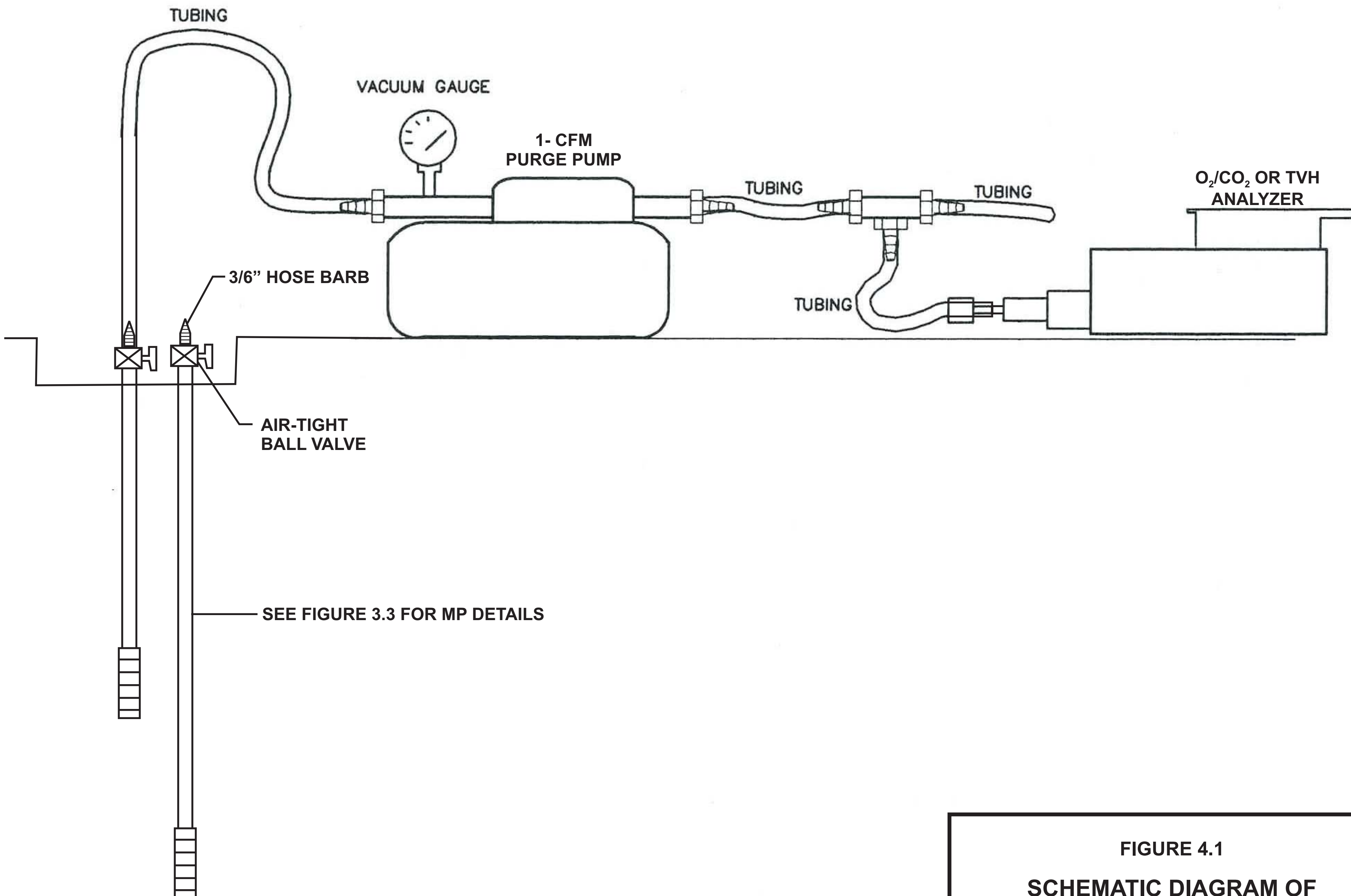


FIGURE 4.1

SCHEMATIC DIAGRAM OF
SOIL GAS PURGING SYSTEM USING
DIRECT METER ANALYSIS

draw\743375 Schematic Diagram.cdr scan pg2 ma 2-4-04

3. Connect Tygon® tubing to a "sampling tee" placed several feet downstream of the pressure side of the purge pump. DO NOT CONNECT THE DETECTOR TO THE SAMPLING TEE YET!

4. With an eye on the vacuum gauge and tubing, turn on the purge pump. After 10 seconds record the vacuum reading and note if the tubing is collapsed or water is being drawn up the MP. If either of these conditions exist, the MP may be located in soil that is too tight or too wet to collect a soil gas sample. If gas seems to be flowing through the pump without the appearance of water go on to Step 5. If you can feel soil gas discharging at the sampling tee and the vacuum reading is above 200 inches of H_2O, the collection of soil gas will be possible but difficult from this MP.

5. With the purge pump still running, connect the O_2/CO_2 detector to the sampling tee. Note that the detector is connected in a manner to sample **from a portion of the gas stream and not sample all of the gas stream.** (Detectors have built-in air pumps to draw the gas through the instrument. Directing all of the purge pump flow to the detector may damage it.).

6. Measure the oxygen levels in the soil gas. Once they appear stable for 10 seconds the purge is complete. Record the final oxygen level and carbon dioxide level. With the purge pump still running, disconnect the O_2/CO_2 detector and connect the TVH detector. Record the TVH reading.

7. Close the MP valve and then quickly turn off the purge pump.

4.1.2 Soil Gas Sample Collection

The purging procedure described above is generally acceptable for sampling soil gas in high-permeability sandy soils. If an oxygen level of 1 percent or less is measured during purging of the MPs, the purging procedure outlined above should be adequate for determining baseline soil gas conditions.

Practice has shown that the quality of the soil gas sample is improved when soil gas does not have to pass through the purge pump before sampling. Even under lower vacuums (<50 inches H_2O), purge pumps are prone to vacuum leaks that can dilute the sample with atmospheric air (oxygen). Purge pump seals can also become tainted with hydrocarbons and "bleed" this residual into your next sample. The procedure described in this section should yield consistent and reproducible soil gas results regardless of soil type.

Figure 4.2 illustrates the most reliable method of soil gas sample collection. After the MP is purged using the procedure in Section 4.1.1, the air tight valve at the top of the MP must be closed before the purge pump is turned off. This prevents leakage of atmospheric air back into the well. The following soil gas sample collection procedure is recommended for all sites, but particularly at MPs that are completed in low permeability or wet soils that have required a vacuum of greater than 50 inches of H_2O to remove soil gas. With practice, this procedure can be accomplished by a single sampling technician. However, two people are recommended if this is your first pilot test.

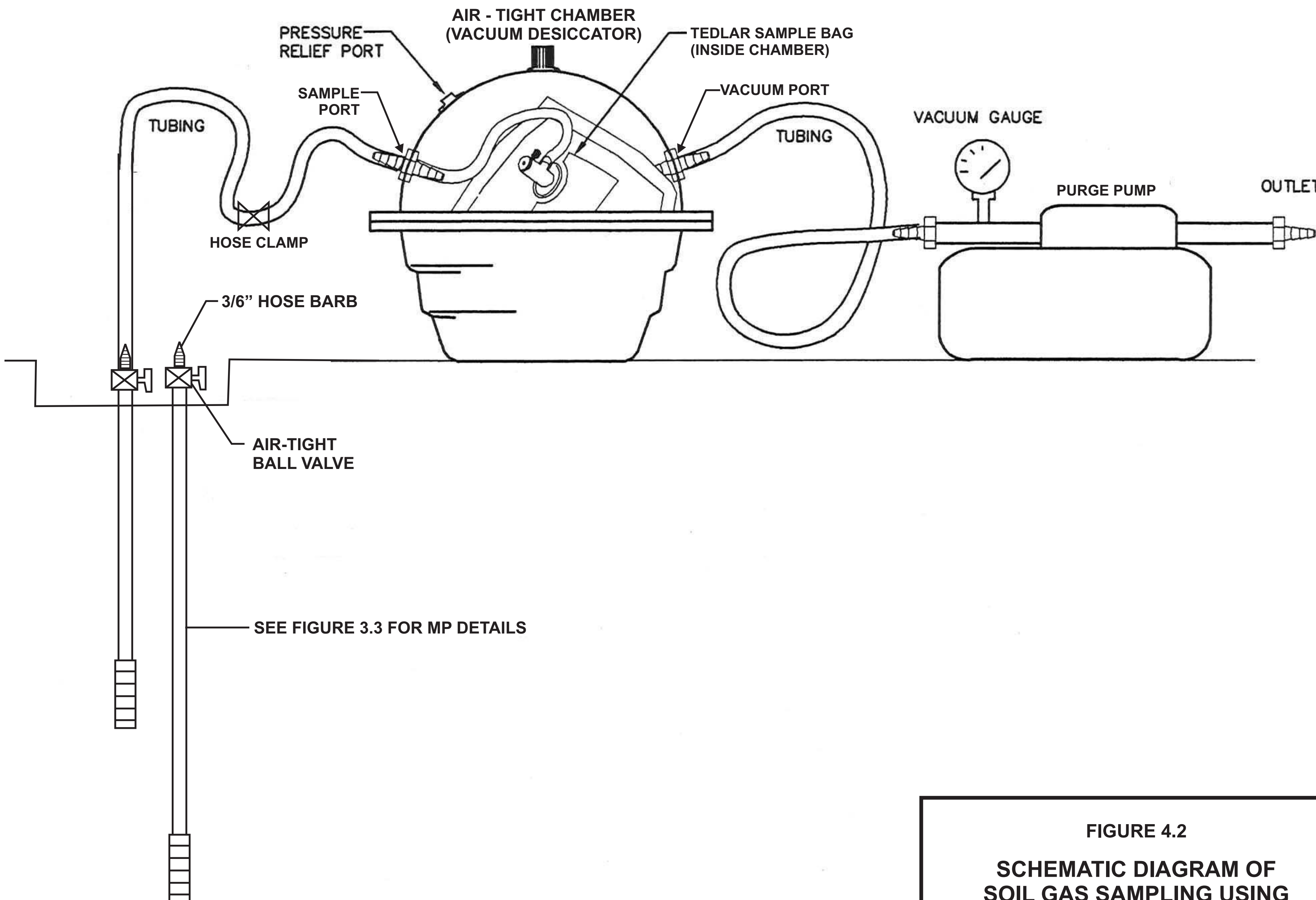


FIGURE 4.2

SCHEMATIC DIAGRAM OF SOIL GAS SAMPLING USING AN AIR-TIGHT CHAMBER

draw\743375 Schematic Diagram.cdr scan pg4 ma 2-4-04

1. Calibrate your O_2/CO_2 and TVH detectors following procedures in Section 3.4.2 and 3.4.3. These instruments must be ready to go. Label a new 3-liter Tedlar® bag with the MP identification number.

2. Prior to using each Tedlar® bag for the first time, check it for leaks. To accomplish this inflate the bag, close the valve, and gently squeeze the bag for 5 to 10 seconds. If the bag deflates, it has a hole in it and should not be used.

3. Evacuate all of the air from the Tedlar® bag and close the valve. Place the Tedlar® bag inside the air tight chamber (desiccator) as shown in Figure 4.2. With the valve on the Tedlar® bag still **CLOSED**, connect it to the vacuum desiccator's sampling hose barb as shown.

4. Purge the MP using the procedures outlined in Section 4.1.1.

5. Following the purge and with the vacuum pump running, close the hose clamp on the tubing near the vacuum pump (if desired the valve at the top of the MP may also be closed). Then disconnect the tubing from the vacuum pump and attach it to the sample port of the desiccators. Take a second piece of tubing and attach one end to the vacuum port on the desiccators and one end to the vacuum pump.

6. Now **OPEN** the valve on the Tedlar® bag, the hose clamp, and the valve at the top of the MP. The two hemispheres of the desiccators are then closed together with the Tedlar® bag inside.

7. Place your finger over the vacuum relief port. This will create a vacuum inside of the air-tight chamber and will begin to fill the Tedlar® bag with soil gas directly from the well.

8. When the Tedlar® bag is 3/4 full, close the hose clamp (and if desired the valve at the top of the MP). This seals off the tubing to the Tedlar® bag and prevents the gas sample from being "sucked" back into the MP.

9. Turn off the purge pump and open the desicator. Immediately close the valve on the Tedlar® bag then remove it from the desiccator. The gas sample is now ready for analysis.

10. Now use your calibrated detectors to determine the O_2/CO_2 and TVH in the soil gas. Using a small length of Tygon® tubing, connect the detector directly to the Tedlar® bag. The detectors have sampling pumps that will draw the sample out of the bag.

11. If BTEX compounds are a concern at the site, a second 3-liter Tedlar® sample can be collected and transferred to a Summa® Canister for shipment for laboratory analysis.

If concentrations of soil gas using the air-tight chamber method are in agreement with samples collected from the discharge of the purge pump, you can conclude that the purge pump does not leak atmospheric air and that additional samples can be accurately collected from the purge pump discharge. Purge pump seals will respond differently under different vacuum and temperature conditions. When in doubt, use the air tight chamber to collect samples. Peristaltic pumps are another option for collecting soil gas samples in low-permeability soils.

The purging and soil gas sample collection procedure should be completed for each MP on the site. A field log should be kept to record the required vacuum, O_2/CO_2 and TVH readings at each MP. A sample log for MP monitoring has been included in Appendix C.

Baseline soil gas sampling will reveal several important facts about the site that need to be considered before proceeding with the remainder of the pilot test. At a "perfect" site, baseline oxygen levels are less than 1 % at all MPs where contamination is known to exist (based on MP boring logs). Carbon dioxide should be elevated above 5%, but there are many sites with alkaline soils where the carbon dioxide produced by in-situ respiration is buffered and becomes a mineral carbonate instead of gaseous phase CO_2. As a result, carbon dioxide is not always a reliable indicator of biological respiration and oxygen is more reliable for respiration calculations. Baseline TVH readings at gasoline and JP-4 sites can be in excess of 10,000 ppmv, while sites with JP-8, Jet-A or diesel may be less than 1000 ppmv. Regardless of the fuel type, there are generally low oxygen readings in areas with high TVH readings. Higher hydrocarbon concentrations generally produce greater bioactivity and higher biological oxygen demands.

4.1.3 Troubleshooting Soil Gas Sampling Problems

Recognizing and fixing soil gas sampling problems is an important aspect of bioventing pilot tests. Table 4.1 lists some of the common indications of soil gas sampling problems and how to fix or compensate for them.

4.2 OXYGEN AND PRESSURE INFLUENCE TESTING

The key to successful bioventing is to ensure that the air injection vent well will supply adequate oxygen to all contaminated soils. As a practical design goal, all contaminated soils should be supplied with at least 5 percent oxygen during full-scale bioventing. The optimized bioventing system will achieve this goal without injecting excessive air. The vent well and MP configuration presented in Figure 3.1 and Table 3.1 is designed to collect the data that is needed to estimate the radius of oxygen influence from the air injection vent well.

Because oxygen is consumed by soil bacteria as the injected air moves radially outward through the soil, it may take a week or more for the true radius of oxygen influence to reach equilibrium. Even longer periods may be required for oxygen to diffuse into contaminated clay layers. Many 1 or 2 day pilot tests have underestimated the final radius of oxygen influence or wrongly concluded that a clay layer was not receiving oxygen. For this reason, a longer period of air injection and a combination of soil gas chemistry and pressure influence readings are recommended for estimating the radius of oxygen influence at a site.

TABLE 4.1
SOIL GAS COLLECTION TROUBLESHOOTING

Indicator	Problem	Solution
Little or no soil gas can be extracted from MP at high vacuums	Soil is too tight or wet to collect soil gas sample.	This MP may have to be sampled during a drier season with lower water table. Be patient and try to collect a soil gas sample using the procedure outlined above.
	The purge pump is not working.	Disconnect the purge pump from the MP tubing and see if it can move air.
Water is pulled up in the sampling tubes	Perched water may have drained into sand pack as a result of drilling.	This MP may have to be sampled during a season with lower water table.
	The MP may have been installed into or too near to the water table	If the water depth is less than 22 feet (or local suction lift limit) it may be possible to suck some of the water out with the purge pump. A sealed water trap will be needed to prevent water from entering and fouling the air purge pump.
Tedlar® bag will not inflate	Valve could be closed on Tedlar® bag	Check valve
	Desiccator O-ring is not properly seated	Reset O-ring
	Tedlar® bag has hole in it.	Check Tedlar® bag for leaks
There are oxygen readings above 5 percent in soils with known contamination.	There may be air leaking into the sample collection system.	Check all tubing, Tedlar bags, fittings, and valves. A positive pressure can be put on the system and the tubing and fittings sprayed with soapy water to detect pinhole leaks. Collect a sample using the desiccators and determine if it matches samples collected from the vacuum pump discharge. If not, replace the vacuum pump.
	There may be a leak in the grout seal above the MP.	Add a layer of water around the top of the MP seal. Reverse the purge pump and inject air into the MP. Watch for bubbles at the surface of the seal. If leak is minor, the seal can sometimes be repaired by pouring a layer of liquid bentonite on top of the existing seal and letting it sit overnight.
	The soil may be naturally aerated.	The upper layer of sandy sites can be naturally aerated. That's good but this MP can't be used for respiration testing.
	You may be over purging the MP. Too long of a purge can draw in oxygen from surrounding clean soils.	Come back to this point in several hours and reduce the purge time to 5 seconds. This may produce lower O_2 readings.
	There are no aerobic bacteria in the soil.	Bacteria have been present at 99+ percent of all test sites including soils in contact with free product.
Oxygen levels recorded during purging are lower than those recorded from the Tedlar® bag sample.	The MP valve was not properly closed after purging and atmospheric air entered the well.	Repeat the well purging cycle and make sure the MP valve is closed before the purge pump is turned off. Resample the MP using the air-tight chamber.
	The connection between the Tedlar® bag and the MP was not tight or the Tedlar® bag was not completely empty before it was placed in the air-tight chamber. Tedlar® bag could have hole in it.	Check all connections. Remove all air from Tedlar® bag before placing it in air-tight chamber. Repeat purge and sample procedures. Check Tedlar® bag for leaks.

The following test procedures and soil gas measurements are recommended for estimating the radius of oxygen influence. Two checklists are provided. The first checklist is for the "extended test." This longer period of air injection will provide the most reliable radius of influence results, particularly in low permeability clay soils. Thesecond checklist is for the "short test" and should provide a good estimate of radius of influence in relatively homogeneous sandy or silt soils.

4.2.1 Extended Pressure/Oxygen Influence Test

If time and budget allow, the extended pressure/oxygen influence test should be used for all sites. This test requires a 14-day air injection period and two field mobilizations. To complete the extended test you will also need a continuous power supply (not a portable generator!). This test will greatly improve the accuracy of oxygen influence estimates in low-permeability soils. Lower soil permeability means lower air injection rates. This will extend the time to reach equilibrium between biological oxygen consumption and oxygen injection rates. The chance of detecting oxygen diffusion into clay layers is also improved in an extended test.

After the initial baseline soil gas conditions are measured at the site, the test blower is connected to the air injection vent well and prepared for operation. The following procedures and measurements are recommended. Start this test in the morning so you will have less need to collect data into the night.

1. Before injecting air into the vent well, open the flow control valve (FCV on Figure 3.4) so that the initial surge of air can be diverted away from the vent well. Turn on the blower system and check to ensure that air is flowing out of the FCV.

2. Slowly close the FCV until all of the air is injected into the vent well. Check the pressure gauge at the well head to make sure that the injection pressure does not exceed the manufacturer's maximum rated pressure.

> ***NOTE**: The pressure relief valve should automatically open in this case.*

3. Using a set of Magnehelic® or equivalent high-quality pressure gauges begin to measure the pressure at each MP, beginning with the MPs closest to the vent well. Record the pressure to the nearest 0.1 of an inch of H_2O and the time of each MP reading. Since the pressure response in the outermost MPs will be small, a gauge capable of reading a 0.01 inch H_2O pressure change is recommended. A test log for pressure and oxygen influence testing is provided in Appendix C. Begin by measuring the pressure response at each MP at 10 to 15 minute intervals until the pressure readings begin to level off.

4. Once the pressure readings are increasing by less than ten percent per 30 minutes you can begin to collect soil gas samples to determine how the soil gas chemistry is changing. Because the MPs are under a positive pressure, it may be possible to use a piece of Tygon® tubing to connect a Tedlar® bag directly to the hose barb at the top of the MP. This eliminates the need for a purge

pump because the soil gas is being forced up the MP and directly into the Tedlar® bag. If the Tedlar® bag will not fill, the well sampling method described in Section 4.1.2 should be used to collect a sample for analysis.

5. Using calibrated O_2/CO_2 and TVH detectors, measure the soil gas chemistry and compare it to the baseline for each MP. A trend of increasing oxygen and decreasing carbon dioxide is normally observed. TVH normally decreases near the vent well but may increase in MPs at the outer edge of the contamination. If this is a gasoline site, ensure that no basements or utility corridors are at risk from vapor migration.

6. After collecting 4 to 6 hours of pressure and soil gas chemistry data, return to the blower instruments and record the vacuum upstream of the blower, the outlet temperature, the pressure downstream of the blower, and measure the air flow into the vent well using a thermal anemometer.

7. If oxygen has already increased by more than 2 percent at the outer MPs you are injecting too much air. Open the FCV so that only half of the flow is directed down the well. Use the thermal anemometer to adjust the FCV and new injection rate. Once stabilized, record the new vacuum, pressure and flow readings at the blower.

8. If all MPs are showing oxygen increases after the first 4-6 hours an extended 14 day injection may not be required. You will have to make a field call based on your schedule and the rate of oxygen increases you observe. Once the MPs in contaminated soil have reached 10 percent oxygen you have completed the oxygen influence test and are ready for the in-situ respiration test.

9. If oxygen is not reaching the outermost MPs or MPs in clay layers you should leave the blower running for approximately two weeks. Return to the site and take a final round of pressure, O_2/CO_2 and TVH readings at each MP as well as the vacuum, pressure, temperature and flow readings at the blower and well head. Leave the blower running and prepare for the in-situ respiration test (See Section 4.3).

***NOTE**: One advantage of an extended pressure/oxygen influence test is that most of the contaminated soil mass will have enough oxygen in the soil gas to be immediately used for the in-situ respiration test. A minimum oxygen level of 10 percent is recommended before starting the in-situ respiration test at a specific MP.*

4.2.2 Short-Term Pressure/Oxygen Influence Test

If budgets and time will not allow the extended test, a shorter test can be completed in 12 to 24 hours. This test may be adequate for small sites with higher permeability soils. Again, short-term tests are not recommended for low-permeability soils.

The short-term test begins exactly like steps 1-7 in the extended test. However, instead of leaving the blower running for two weeks, the blower is left on overnight or for at least 12 hours. In the short-term test, the final round of pressure readings in the outer MPs must be carefully recorded to the nearest 0.01 inches of H_2O. In very contaminated soils, the oxygen may be consumed before it reaches the outermost MPs. In this case, increases in pressure may be useful in showing that the oxygen will eventually reach these outer MPs once the oxygen demand is at equilibrium with the oxygen injection rate.

One disadvantage of a short-term oxygen influence test is that many of the MPs may not have enough oxygen in the surrounding soil gas to be immediately used for the in-situ respiration test. A minimum oxygen level of 10 percent is recommended before starting the in-situ respiration test at a specific MP. The next section describes how oxygen can be selectively added to the soil surrounding a specific MP if the oxygen influence test fails to provide the 10 percent oxygen that is required.

4.3 IN-SITU RESPIRATION TESTING

4.3.1 Principles of In-Situ Respiration

The in-situ respiration test was developed to provide a quick method of estimating in-situ biodegradation rates. The test provides an estimate of the potential for aerobic biodegradation of the petroleum hydrocarbons at this site. Although the microbial processes involved in the degradation of hydrocarbons are complex, the in-situ respiration test provides a simplified method of correlating oxygen uptake to the rate of hydrocarbon mineralization to carbon dioxide and water. For example, the stoichiometric equation for the microbial degradation of n-hexane is as follows:

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

Based on this equation, 9.5 moles of oxygen are required for every mole of n-hexane degraded. On a weight basis, approximately 3.5 grams of oxygen are required to degrade one gram of n-hexane. This ratio of 3.5 to 1 is a good average for all petroleum hydrocarbon degradation and allows us to estimate the rate of hydrocarbon degradation by simply measuring the rate at which oxygen is being consumed in the soil gas. Section 4.4 provides additional information on how to calculate in-situ respiration rates. The *Principles and Practices of Bioventing Volumes I and II* provides a more in depth discussion of this topic.

Experience has shown that initial rates of biodegradation tend to be higher than rates measured after several months of bioventing. For example, the average initial biodegradation rate measured at the 142 Air Force test sites was 1200 mg of TPH degraded per kilogram of soil per year. Following one year of bioventing, the rate had dropped to an average of 700 mg TPH per kg soil per year (AFCEE, 1996). This decrease is often due to the decrease in hydrocarbon bioavailability over time. Water soluble BTEX and other low molecular weight compounds will quickly biodegrade, leaving the higher molecular weight and less soluble compounds to degrade at a slower rate.

__NOTE:__ The use of initial TPH biodegradation rates will overestimate the annual rate of TPH removal and could lead to blower overdesign to meet high oxygen utilization rates. Respiration rates measured after one year of bioventing will provide a more conservative estimate of TPH removal overtime.

4.3.2 In-Situ Respiration Test Procedures

The in-situ respiration test can be most efficiently completed immediately following the pressure/oxygen influence testing described in Section 4.2. With the blower still running, the final round of pressure, O_2/CO_2, and TVH readings should be collected for the pressure/oxygen influence test. Not all MPs should be used for respiration testing. For best results, MPs selected for in-situ respiration tests should:

- Be located in contaminated soil,
- Have baseline oxygen readings of less than 2 percent,
- Be aerated to at least 10 percent oxygen as a result of pressure/oxygen influence testing, and
- A minimum of three MPs should be used and at least two MPs from each contaminated soil type (sand, silt, clay layers).

If a MP is located in contaminated soil and the soil gas has not yet been aerated to 10 percent oxygen, the oxygen at that MP can be quickly increased by injecting air directly into the MP. This additional oxygen is provided by using a 1-cfm air pump to inject atmospheric air into the MP for a period of at least 12 hours. Multiple 1-cfm air pumps may be required for multiple MPs. This injection should take place with the main pilot test blower still injecting air into the central vent well.

Once the MPs for in-situ respiration testing have all been aerated to contain at least 10 percent oxygen, the following procedure should be used to collect soil gas samples and complete the respiration test. Recommend starting the in-situ respiration test in the early morning to reduce the need for night time sampling.

1. Make sure you have calibrated your O_2/CO_2 and TVH detectors and have a supply of clean Tedlar® bags available. Prepare the purge pump and accessories for soil gas purging and sampling as illustrated in Figure 4.1 and 4.2.

2. Collect an initial round of O_2/CO_2 and TVH samples from the selected MPs with the main blower running. Use the sample collection methods in Section 4.1.2. Once these samples are collected, **turn off the blower** to stop the supply of oxygen to the soil.

3. Turn off any 1-cfm air pumps that are being used to provide oxygen to individual MPs, and then immediately collect a soil gas sample from each of these MPs using the sample collection methods in Section 4.1.2.

4. Fill in the initial O_2/CO_2 and TVH readings on the in-situ respiration data log provided in Appendix C. Make sure you note the time of each soil gas sample.

5. Immediately after the initial round of MP soil gas samples, repeat the round of sampling in the same order that the MPs were sampled in the initial round. It is important to be use short (10 second) and consistent purge times for all MPs. Over purging will pull in soil gas from clean areas and add unwanted oxygen to the MP.

6. Note the MPs that have faster and slower rates of oxygen utilization. For MPs that are utilizing more than 2 percent of oxygen per hour, continue hourly sampling. For MPs that are utilizing less than 2 percent per hour recommend that samples be collected every 2-3 hours. The first 12 hours of an in-situ respiration test provide the most useful data. A minimum of four samples should be collected in the first 12 hours from all MPs. If time permits, soil gas samples should be collected for a 24-hour period.

7. Create your own simple graph of oxygen concentrations vs. the time since blower shut down. This data will produce an oxygen utilization curve. Section 4.4 provides an example data plot. Each MP will probably show a different rate of oxygen utilization. MPs in the center of the contamination will tend to utilize oxygen faster than MPs on the fringe of the contamination.

4.4 DATA ORGANIZATION

Appendix C provides three test logs for organizing baseline soil/soil gas results, pressure/oxygen influence test results, and in-situ respiration results discussed in Sections 4.1, 4.2 and 4.3 respectively. The purpose of this section is to illustrate how this data is organized for full-scale design evaluations. For additional information on how to use this data for full-scale design decisions, the reader is referred to the *Principles and Practices Manual Volume II.*

4.4.1 Baseline Soil and Soil Gas Data

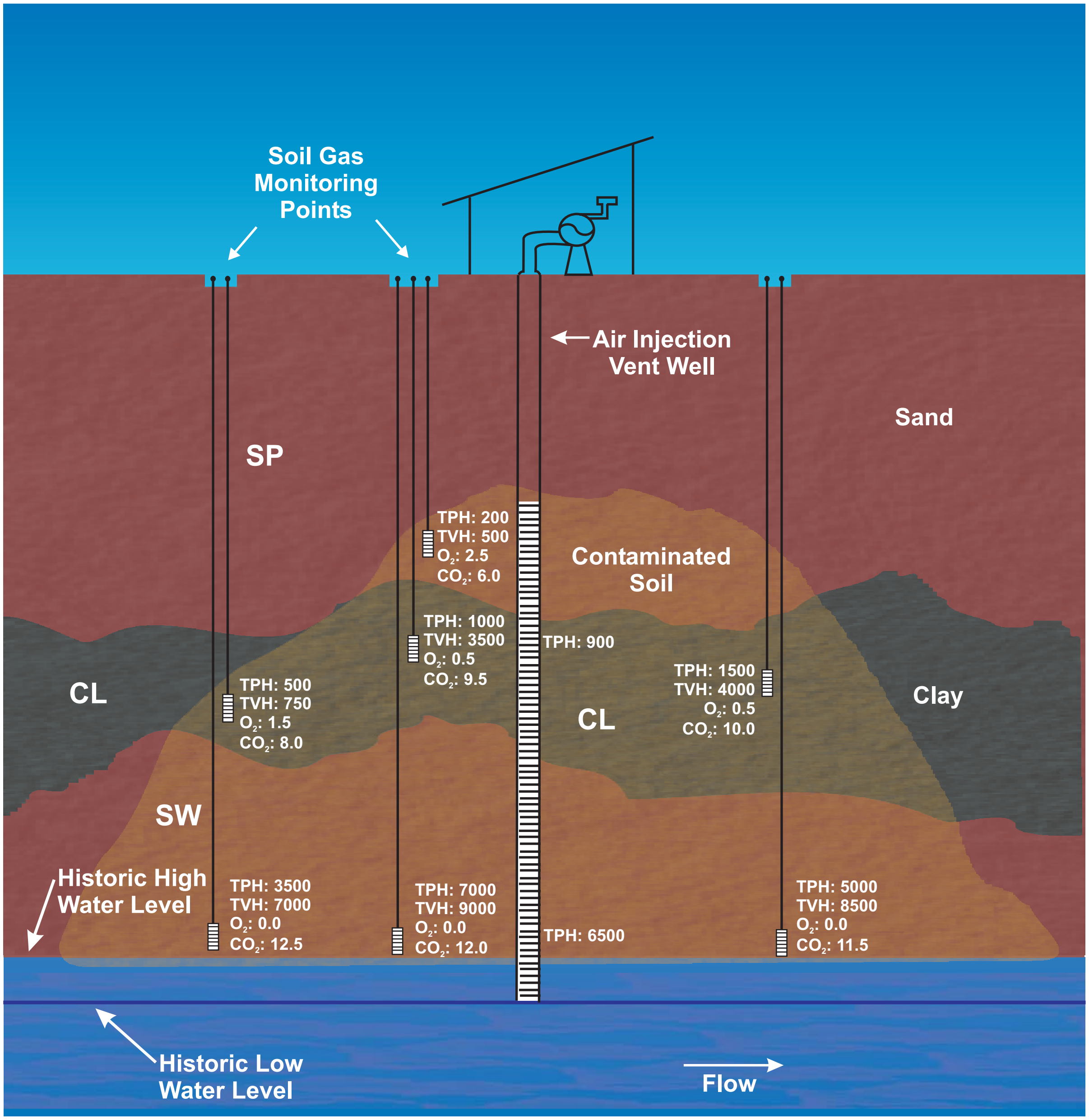
Baseline soil and soil gas results are very important for determining the areas and depth intervals at the site that are most contaminated and areas that are most in need of bioventing. This data is very useful for determine the most effective placement of future vent wells and MPs to monitor full scale bioventing progress. The best method of organizing this data for analysis is in a site cross section that can be constructed from the boring logs, soil sampling results and initial soil gas data. Figure 4.3 shows a site cross section that combines initial site data into a single visual image.

4.4.2 Radius of Pressure/Oxygen Influence

Estimating the radius of oxygen influence at equilibrium is very difficult to do without an extended period of air injection. The extended 14-day injection can greatly improve the accuracy of the radius of influence estimate, particularly in low permeability soils. Figure 4.4 illustrates the 14-day change in pressure and soil gas chemistry data from three MPs located at 10, 20 and 40 feet from the central injection vent well. In this case, the soils are predominantly silts and clays and these MPs are all located at approximately the same depth. This graphic is useful because changes in pressure response and soil gas chemistry can be visualized at increasing distances from the vent well.

FIGURE 4.3

SOIL AND SOIL GAS DATA CROSS-SECTION



LEGEND

TPH (MG/KG)

TVH (ppmv)

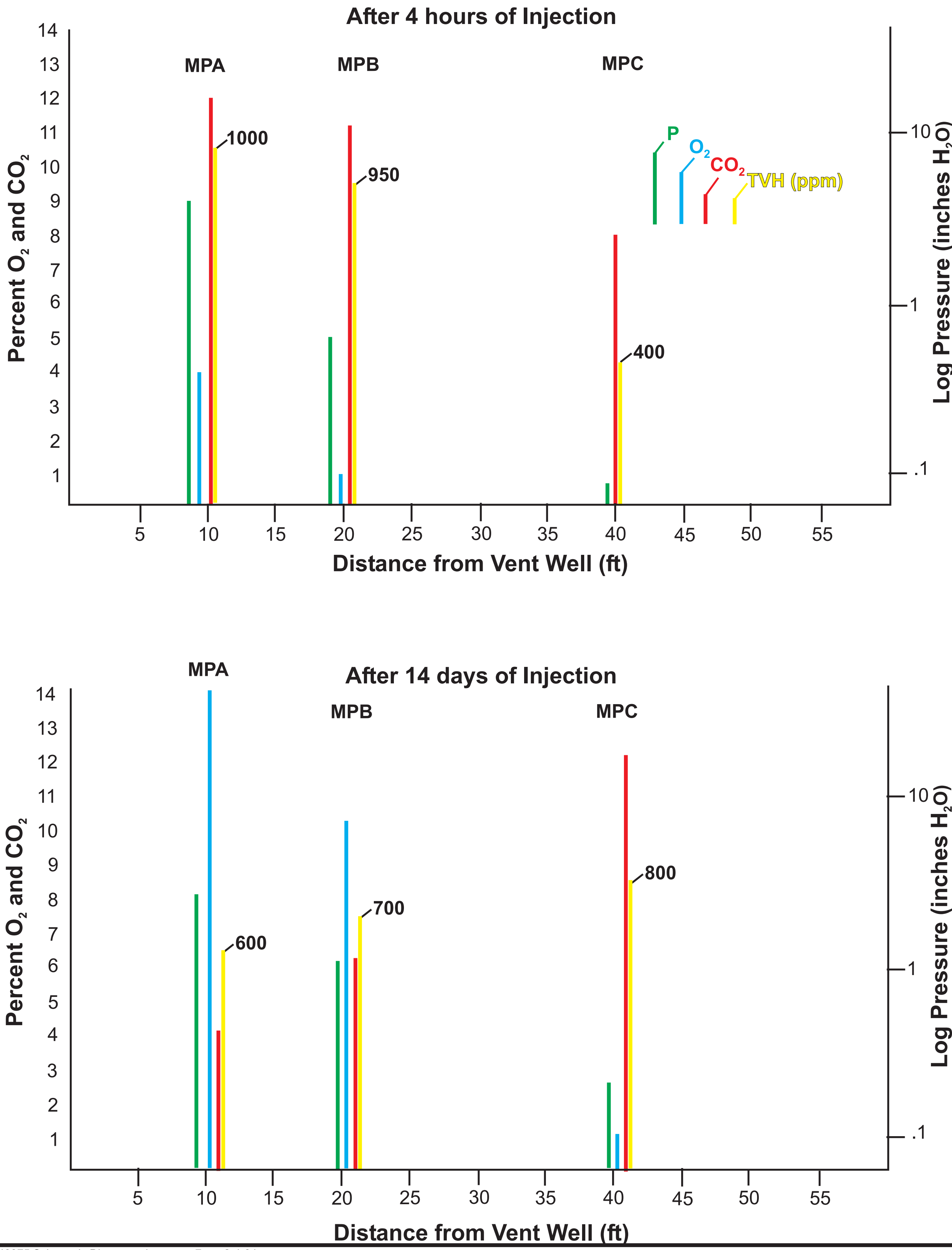
O_2 (%)

CO_2 (%)

draw\743375 Basic Bioventing Design .cdr pg2 ma 2/3/04

FIGURE 4.4

OXYGEN INFLUENCE GRAPHIC



draw\743375 Schematic Diagram.cdr scan pg7 ma 2-4-04

Figure 4.4 shows two "snap shots" in time for the three MPs. The first chart illustrates the pressure and soil gas chemistry after 4 hours of air injection, and the second chart the outermost after 14 days of injection. In this example, there is still less than 2 percent oxygen in the vapor point MPC after 14 days of air injection, however there are indications that air flow is occurring at the outermost MPC. Pressure readings at MPC have increased by a factor of three to over 0.1 inches of H_2O and CO_2 and TVH levels have increased. It appears that the CO_2 and TVH from near the vent well are being pushed outward in the vicinity of MPC. MPC is clearly within the pressure radius of the vent well and soil gas is changing in a logical pattern. Although oxygen is still below the desired 5 percent at MPC, there are positive indications that oxygen levels will continue to increase at the 40-foot radius.

Based on this data, it appears that oxygen influence will be achieved at 40-foot radius if the full-scale blower operates at this air injection rate.

The *Principles and Practices Manual Volume II* offers additional quantitative tools for estimating the theoretical radius of oxygen influence based on the measured rates of oxygen utilization and the injected air flow rates. These tools are particularly useful for estimating the radius of oxygen influence from limited, short-term test data. Graphics like Figure 4.4 offer a visual method of analysis that is particularly suited for extended air injections.

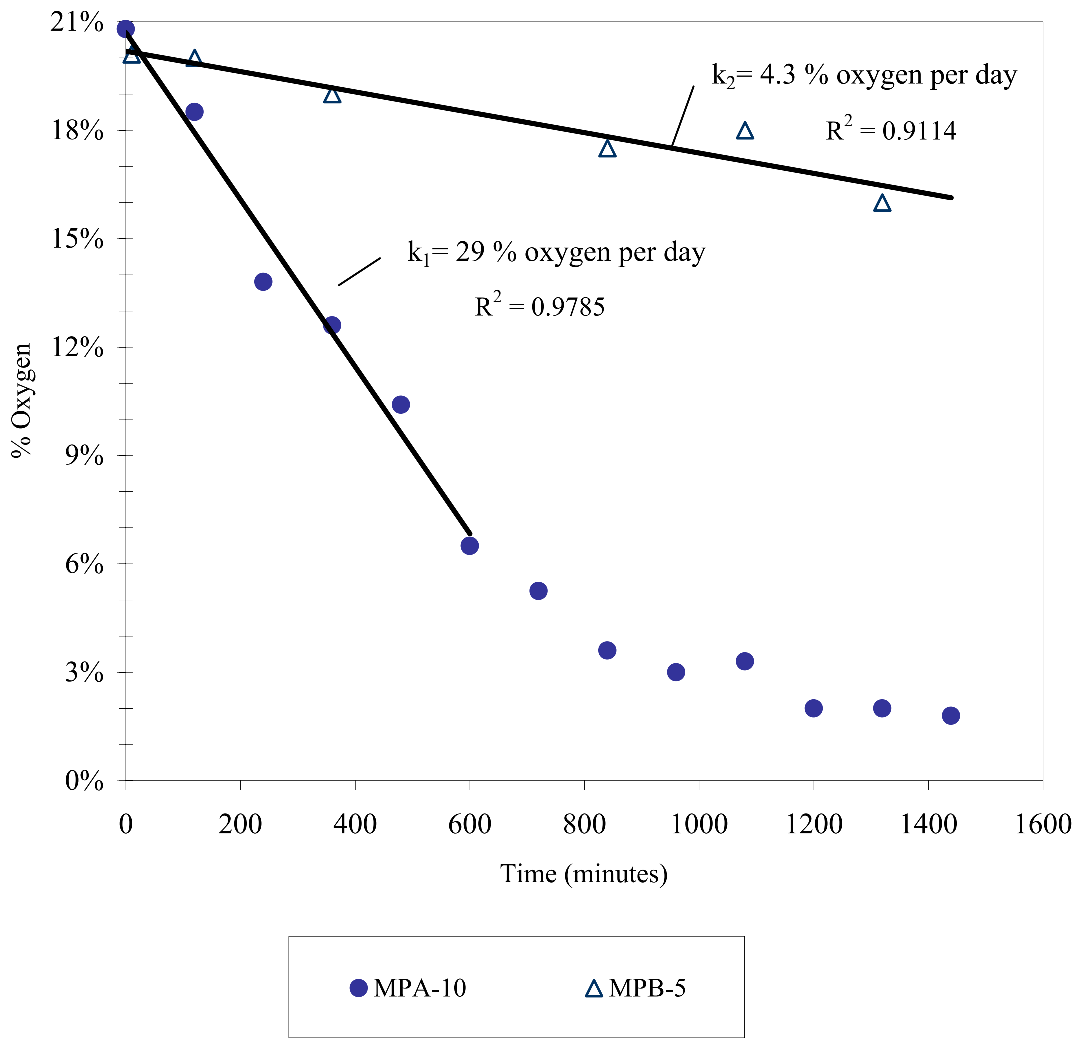
> ***NOTE:*** *If the pilot vent well and MPs are sufficient to provide oxygen to and monitor the entire site, the full-scale system can be established by purchasing and installing a similar, more permanent blower system. The blower system should be protected from the weather in a simple enclosure and a certified electrician should complete a more permanent power connection.*

4.4.3 In-situ Respiration Test Data

The rate of oxygen utilization is the key data produced from the in-situ respiration test. Carbon dioxide production is of interest, but is not as reliable for the reasons already stated in Section 4.1.2. Figure 4.5 illustrates the common method of analyzing oxygen utilization data. Excel© or similar spreadsheet and graphing software can be used to plot and analyze the oxygen vs. time data for each MP. The $\mathbf{k_o}$ value is calculated from the slope of the line and assumes a "zero order" relationship because oxygen is not limiting the biodegradation. The plot of MPA-10 oxygen data shows a rapid linear decrease in oxygen followed by a "flattening" of the oxygen utilization slope once the oxygen drops below 5 percent. This is common in very contaminated soils because at lower oxygen concentrations, oxygen may begin to limit the rate of biodegradation. The steep linear portion of the oxygen utilization curve should be used to calculate the $\mathbf{k_o}$ and the rate of biodegradation.

At MPA-10, a $\mathbf{k_o}$ of 29% per day was calculated. For MPB-5, a $\mathbf{k_o}$ of 4.3 % per day was calculated. In this example, MPA-10 has a high $\mathbf{k_o}$ because it was located near the center of the fuel spill and within the highly contaminated smear zone at 10 feet bgs. A lower $\mathbf{k_o}$ was observed at MPB-5. MPB-5 was located in a less contaminated area at a depth of 5 feet. It is not uncommon for the rate of oxygen utilization to vary by more than an order of magnitude at the same site. Higher $\mathbf{k_o}$ values are commonly recorded in soils

FIGURE 4.5
OXYGEN UTILIZATION RATES



with higher levels of hydrocarbon contamination which support larger populations of bacteria. Since degradation rates are higher in more contaminated areas and lower in less contaminated areas, the total time required to clean up the entire site tends to equal out over time.

The $\mathbf{k_o}$ value for each MP can be used to estimate the rate of hydrocarbon biodegradation ($\mathbf{k_B}$) from the equation:

$$k_B = \frac{-k_o}{100} \frac{\theta_a \rho o_2 C}{(\rho_k)}$$

where: k_o = the rate of oxygen utilization (% oxygen/day)

θ_a = the gas-filled porosity of the soil (unitless)

ρ_{O2} = oxygen density (mg/L)

ρ_k = the soil bulk density (g/cm^3)

C = hydrocarbon to oxygen ratio (1/3.5 or .29)

$\mathbf{k_B}$ = the rate of hydrocarbon biodegradation (mg TPH/kg soil/per day)

Physical soil measurements such as soil type, bulk density (ρ_k), and moisture content are required to to provide a reasonable estimate of gas filled porosity (θ_a) and $\mathbf{k_B}$. These soil parameters are normally measured in soil samples collected from vent well and MP borings (see Section 3.3). Tables of ρ_{O2} and ρ_k values, along with additional information on calculating and interpreting $\mathbf{k_B}$ can be found in the *Principles and Practices Manual Volume I.*

> ***NOTE:*** *Do not estimate TPH cleanup times based on initial rates of biodegradation (see Section 4.2.1) because degradation rates will generally decrease overtime.*

SECTION 5

MAINTAINING, MONITORING, AND CLOSING BIOVENTING SITES

This section provides recommendations for maintaining and determining the long-term performance of bioventing systems. The soil gas and in-situ respiration monitoring techniques used for extended monitoring are identical to those described in Section 4. This section discusses the interpretation and use of this data to evaluate the performance and progress of the full-scale bioventing system toward achieving site cleanup goals.

5.1 SYSTEM MAINTENANCE

Bioventing systems are intended to be very simple to operate and maintain. These systems are normally designed to operate 24 hours a day and 7 days a week. Power outages are the single greatest threat to successful bioventing operations. Small blowers of less than 5-hp should be directly wired to an on/off switch and fuse box without a starter. This allows the blower to automatically restart when power returns to the line. Larger blowers using 3-phase power generally have starters that require manual restarts after power outages. Consult a certified electrician on how to minimize power interruptions to the blower. Regardless of the power supply, someone should check the blower once a month to make sure it is operating.

If a blower will not restart, there is a high likelihood that the motor is burned out. Most small blowers have a one-year warranty and will have an operating life of 2 to 3 years. If a small blower is more than two years old, it is generally more cost effective to buy a new blower than to repair the old one. It may be more cost effective to repair larger blowers.

5.1.1 Basic Maintenance Checklist

- Record the temperature, vacuum, and pressure readings during every maintenance check and compare with past readings. Increases in temperature or vacuum could indicate a clogged air filter. Increases in injection pressure could indicate a wet soil condition. Decreases in injection pressure could indicate a leak in the injection piping, the vent well seal, or a drying out of soil near the screen.

- Most small regenerative blowers are sealed and do not require lubrication. Many pneumatic or/positive displacement blowers do require regular lubrication. Follow the manufacturer's lubrication and maintenance schedule.

- Air injection systems should be equipped with air filters to reduce the wear and tear on the blower due to dust particles. In dusty areas, air filters should be changed on a quarterly or semi-annual basis. In low dust areas, annual filter changes are recommended to extend blower life.

- Check all piping, valves and gauges for air leaks. Air injection systems may settle in unconsolidated soils, creating stress cracks in air injection piping.

- Check the general condition of MPs and the flush mount covers that protect them. Don't let water accumulate in the MP well box as this can crack MPs during freezing conditions. Close the air-tight valves on top of the MP when not in use.

5.2 PERFORMANCE MONITORING

Performance monitoring of bioventing sites is recommended twice during the first year and annually thereafter. Both soil gas chemistry and in-situ respiration rates can be used to inexpensively evaluate the performance of bioventing systems. The soil gas and in-situ respiration monitoring techniques used for extended monitoring are identical to those described in Section 4. The following paragraphs describe a routine monitoring sequence for all bioventing sites.

5.2.1 Soil Gas Chemistry With The Blower Operating

After arriving at the site, check the blower temperature, inlet vacuum, and outlet pressure readings. Using a thermal anemometer, record the air velocity, and calculate a flow rate into the vent well. Record all of these readings on the data log found in Appendix C. With the blower still operating, collected a round of soil gas data from each of the MPs. Note that purging may not be required if the MP has sufficient positive pressure to directly fill a Tedlar® bag.

Key Performance Indicator: With the blower running, all MPs in contaminated soils should have an oxygen level of at least 5 percent. This will ensure that oxygen is not limiting biodegradation. TVH should also be measured with the system running.

Corrective Action: If one or more of the contaminated MPs contain less than 5 percent oxygen, the air injection flow rate needs to be increased. If this is a multiple vent well system, more of the air flow can be directed to the vent well nearest the oxygen deficient area. If this is a single vent well system, make sure that the FCV and PRV are both closed. A higher horsepower or higher pressure blower may be required. On sites with capillary fringe contamination, oxygen flow may be seasonally restricted by wet soils. In this case, it may only be feasible to biovent capillary soils during the dry seasons.

5.2.2 In-situ Respiration Test

Following the soil gas analysis, turn off the blower system and complete an in-situ respiration test following the procedures in Section 4.3. Collect the respiration data on the same MPs as were used for the initial respiration test. A data log is provided in Appendix C.

Key Performance Indicators: The rate of oxygen utilization at each MP should be compared to the initial rates measured during the pilot test. These k_o values can be converted to fuel biodegradation rates (k_B) using the same soil air filled porosity and bulk density data that was used for the pilot test calculations. Biodegradation rates normally decrease over time as the less biodegradable fraction of the fuel remains behind to be degraded at a slower rate. It is not unusual for the six-month biodegradation rates to be one-half the initial rates. When oxygen utilization rates at all MPs have decreased by an order of magnitude below initial rates, the site should be considered for soil sampling to confirm TPH reductions.

5.2.3 Final Soil Gas Chemistry Rebound

At the end of the in-situ respiration test, a final set of soil gas samples should be collected for TVH analysis. These TVH levels can be compared to the initial site TVH values at each MP and to the TVH levels measured during this monitoring event with the blower running. If benzene is a contaminant of concern at the site, a Summa® canister should be filled with a gas sample from the MP with the highest TVH reading.

Key Performance Indicator: A drop in TVH over time should be observed at all MPs. Note that decreases in TVH do not necessarily equate to an equivalent decrease in TPH in the soil. Volatile compounds tend to be more degradable compounds and TVH may not represent the less biodegradable TPH residuals. Persistent TVH readings could indicate a layer of free product or fuel that is not being treated with the bioventing system. In active fueling areas, a persistent TVH reading could indicate that the fueling system is still leaking.

Corrective Actions: First check to see if free product remains in any groundwater monitoring wells at the site. If so, this is the likely source of persistent TVH readings. If this is an active fueling system, check to see if it has been recently leak tested. If not, recommend a leak test to the facility manager. Continue to operate the bioventing system.

Key Performance Indicator: If benzene is no longer present in the soil gas at levels above 1 ppmv, the remaining level of benzene should be compared to risk-based standards that are appropriate for the current land use. At jet fuel and gasoline sites, BTEX compounds are removed at a much faster rate than TPH and risk-based standards can generally be achieved within the first year of bioventing. Although soil gas sampling provides the most reliable indication of BTEX residuals, most states still require confirmation soil sampling.

5.3 BIOVENTING SITE CLOSURE

The reader is referred to the Air Force *Handbook for the Remediation of Petroleum-Contaminated Sites* on the AFCEE website for a detailed discussion of site closure strategies. Bioventing sites can be closed by meeting a prescribed numerical cleanup standard for TPH or specific standards for compounds such as benzene. In most states, petroleum sites can be closed using more site-specific, risk-based cleanup criteria. These criteria are based on potential exposure to the fuel residual and make allowances for industrial and commercial land use. Before attempting any soil sampling at the site, contact the regulatory agency with oversight responsibility for the site and determine:

- if a risk-based soil cleanup criteria can be used for the site,

- if soil gas samples and a lack of in-situ respiration can be used to gain site closure approval, or

- the number and location of soil samples that will be required to demonstrate that site closure criteria have been met.

An accurate record of bioventing operations and routine monitoring results will demonstrate how the bioventing system has progressed toward site cleanup.

APPENDIX A

USING SOIL GAS SURVEYS TO DETERMINE BIOVENTING FEASIBILITY AND NATURAL ATTENUATION POTENTIAL

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SECTION A1

BACKGROUND

A1.1 OVERVIEW

The objective of this appendix is to provide the reader with a working knowledge of how soil gas can be used as an indicator of subsurface hydrocarbon contamination and how bioventing feasibility can be determined using soil gas monitoring techniques. This appendix has been organized into five sections including this background section. Section A2 describes the mechanical aspects of soil gas monitoring, the use of soil gas probes, and construction of more permanent monitoring points. Section A3 explains how soil gas data are interpreted to indicate bioventing feasibility, and Section A4 describes how soil gas data can be used to design pilot- or full-scale bioventing systems. Section A5 lists the references cited in this addendum.

A1.2 SOIL GAS CHEMISTRY

The chemical composition of soil gas can vary considerably from atmospheric composition as a result of biological and mineral reactions in the soil. Although numerous compounds and elements may be present in soil gas as a result of specific soil and bedrock geochemistry, three indicators are of particular interest in the bioventing context: oxygen, 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.

Oxygen serves as a primary electron acceptor for soil microorganisms employed in the degradation of both refined and natural hydrocarbons. Following a hydrocarbon spill, soil microorganisms begin to use available soil gas oxygen. As the population of fuel-degrading microorganisms increases, the supply of soil gas oxygen is often depleted, creating an anaerobic volume of contaminated soil. Under anaerobic conditions, fuel biodegradation generally proceeds at significantly slower rates. 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 biodegradation of natural or refined hydrocarbons, and can also be produced or buffered by the soil carbonate cycle (Ong *et al*., 1991). Carbon dioxide levels in soil gas are generally elevated in fuel-contaminated soils when compared to levels in clean background soils. However, due to the buffering capacity of alkaline soils, the relationship between contaminant biodegradation and carbon dioxide production is not always a reliable indicator. In acidic soils, such as exist at Tynda1l Air Force Base (AFB), Florida, carbon dioxide production was directly proportional to oxygen utilization (Miller and Hinchee, 1990). Volatile hydrocarbons found in soil gas can also provide valuable information on the extent and magnitude of subsurface contamination. Fuels such as gasoline, which contain a significant fraction of C6 and lighter compounds, are easily detected using soil gas monitoring techniques. Heavier fuels, such as diesel, contain fewer volatiles and are more difficult to locate based on volatile hydrocarbon monitoring. Methane is frequently produced as a by-product of anaerobic biodegradation and, like oxygen depletion, can also be used to locate the most contaminated soils at a site. Extensive literature is available on soil gas survey techniques for using volatile hydrocarbons as indicators of contamination (Rivett and Cherry, 1991; Deyo *et al.,* 1993). Section A3 explains how soil gas hydrocarbons can be used to better delineate potential bioventing sites.

A1.3 ADVANTAGES AND LIMITATIONS

The use of soil gas to determine bioventing feasibility and bioventing progress has several economic and technical advantages over more traditional drilling and soil sampling techniques. In shallow (<20 feet), predominantly sand soils, the labor and equipment cost for a two-person soil gas survey team is approximately one-third the cost of a three-person conventional drilling and sampling team. Many new hydraulically driven, multi-purpose probes can be used for soil gas sampling, as well as for collecting soil and groundwater samples at depth. These probes can be advanced as quickly as conventional augers and do not produce drill cuttings which require expensive analysis and disposal.

An additional advantage of soil gas sampling is that a properly collected gas sample can represent the average chemistry of several cubic feet of soil as compared to a discrete soil sample, which can only describe a few cubic inches of the subsurface. This advantage is of particular importance in risk-based remediation projects where the degree of benzene removal can most accurately be determined by using multiple soil gas sampling locations.

Soil gas techniques have several limitations which must be acknowledged if this approach is to be properly applied. Soil gas monitoring is often impossible in very moist soils and particularly in fined-grained units. Attempts to gather soil gas samples from low-permeability soils often result in the leakage of atmospheric air into the sampling system and inaccurate sampling results.

Although hydraulically driven probes such as cone penetrometers are extending the depth of application, deep contamination and contamination in tight or cobble soils can best be assessed by using standard drilling techniques to install permanent soil gas monitoring points.

Once installed, the spatial orientation of soil gas points in relation to actual fuel-contaminated soil can provide false-positive or false-negative readings, particularly when volatile hydrocarbons are the only analyte. Soil heterogeneities such as clay layers can prevent migration of volatiles from deeper contaminated intervals to shallow soil gas points. Conversely, volatile hydrocarbons can diffuse great distances through very permeable soils, creating volatile soil contamination far from the source area. Because degradation of volatile hydrocarbons exerts a significant oxygen demand in subsurface soils, bioventing wells may be mistakenly sited in soils which actually contain very little adsorbed or free-phase hydrocarbons.

SECTION A2

SOIL GAS INVESTIGATION METHODS

A2.1 INTRODUCTION

This section describes the test equipment and methods that are required to conduct field soil gas surveys, to monitor soil gas for bioventing systems, and to install temporary and permanent 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 states, all permanent monitoring points must comply with well installation regulations.

A2.2 SOIL GAS SURVEYS

Soil gas surveys can be conducted at potential bioventing sites prior to locating the pilot test vent well(s) and monitoring points. Soil gas surveys are particularly useful at sites where the area of contamination is not well-defined. The objective of the soil gas survey is to determine the areal extent and, in the case of shallow contamination, the vertical extent of soil contamination. These data are used to locate the vent well and soil gas monitoring points (MPs), and to determine the optimum depths of screened intervals. Additionally, the survey is used to determine if bioventing is required based on whether or not anaerobic soil gas conditions exist. If sufficient oxygen is naturally available and distributed throughout the subsurface, bioventing may not be required to enhance fuel biodegradation rates.

A2.2.1 Location of Soil Gas Points

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 progress outward to the limits of significant detectable soil contamination. In many cases, soil gas measurements should 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 feet, or if contamination is suspected in different soil types.

A2.2.2 Soil Gas Probes and Installation Techniques

Soil gas sampling is conducted using small-diameter [approximately 5/8- to 1- inch outside-diameter (OD)] steel probes. The typical probe consists of a drive point with a retractable, perforated tip that is threaded onto a series of drive rod extensions (Figure

A2.1). The soil probe is fitted with a replaceable stainless steel screen to prevent fine-grained soils from clogging the perforations. Before use, 1/8-inch-diameter flexible tubing is connected to the soil probe and passed through the center of the drive rods. The 1/8-inch tubing, which is used to collect soil gas samples, extends from the soil probe to the purge pump at the surface. This probe design greatly reduces the chance of vacuum leaks and is highly recommended for bioventing applications.

The method of probe installation will be dictated by soil conditions and depth of contamination. A digging permit from the host Air Force base and utility clearances from the local utility companies should be obtained prior to probe installation. Temporary probes are installed using either a hand-driven electric hammer or a hydraulic ram. The maximum depth for hammer-driven probes is typically 10 to 15 feet, depending on soil texture. Hydraulic rams are capable of driving the probes over 30 feet in a variety of soil conditions.

At sites with deeper contamination, where soil texture precludes the use of a hammer or hydraulic ram or where a permanent monitoring system is required, permanent soil gas MPs may be installed using either a portable or truck-mounted drill rig. Permanent MPs are discussed in Section 3 of the main document.

A2.3 FIELD INSTRUMENTATION AND MEASUREMENTS

Sections A2.3.1 through A2.3.4 discuss the equipment used for soil gas measurements. Additional discussion of this topic is included in Section 3 of the main document.

A2.3.1 Oxygen and Carbon Dioxide

Gaseous concentrations of oxygen and carbon dioxide are analyzed using an O_2/CO_2 direct reading meter. The meter will generally have an internal battery-powered sampling pump and range settings of 0 to 25 percent for both 0_2 and $C0_2$. Prior to taking measurements, the meter should be checked for battery charge level and should be calibrated daily using atmospheric concentrations of 0_2 and $C0_2$ (20.9 and 0.05 percent, respectively) and a gas standard containing 0.0 percent 0_2 and 5.0 percent $C0_2$.

A2.3.2 Volatile Hydrocarbon Concentration

Total volatile hydrocarbon (TVH) concentrations can be analyzed using a variety of hydrocarbon meters. The meter must be capable of measuring hydrocarbon concentrations in the range of 1 to 10,000 parts per million, volume per volume (ppmv) and be capable of distinguishing between methane and non-methane hydrocarbons. Although flame ionization detectors are the most accurate instruments for fuel hydrocarbons, platinum catalyst detectors are also acceptable and are easier to use in the field. Photoionization detectors are not recommended for the high levels of volatile hydrocarbons found at many sites. Prior to taking measurements, the battery charge level should be checked and the meter should be calibrated against a hexane calibration gas to ensure proper operation.

The meter should also have a selector switch to change the response to eliminate the contribution of methane gas to the TVH readings. Methane gas is a common constituent of anaerobic soil gas and is generated by degrading manmade or natural hydrocarbons. If the

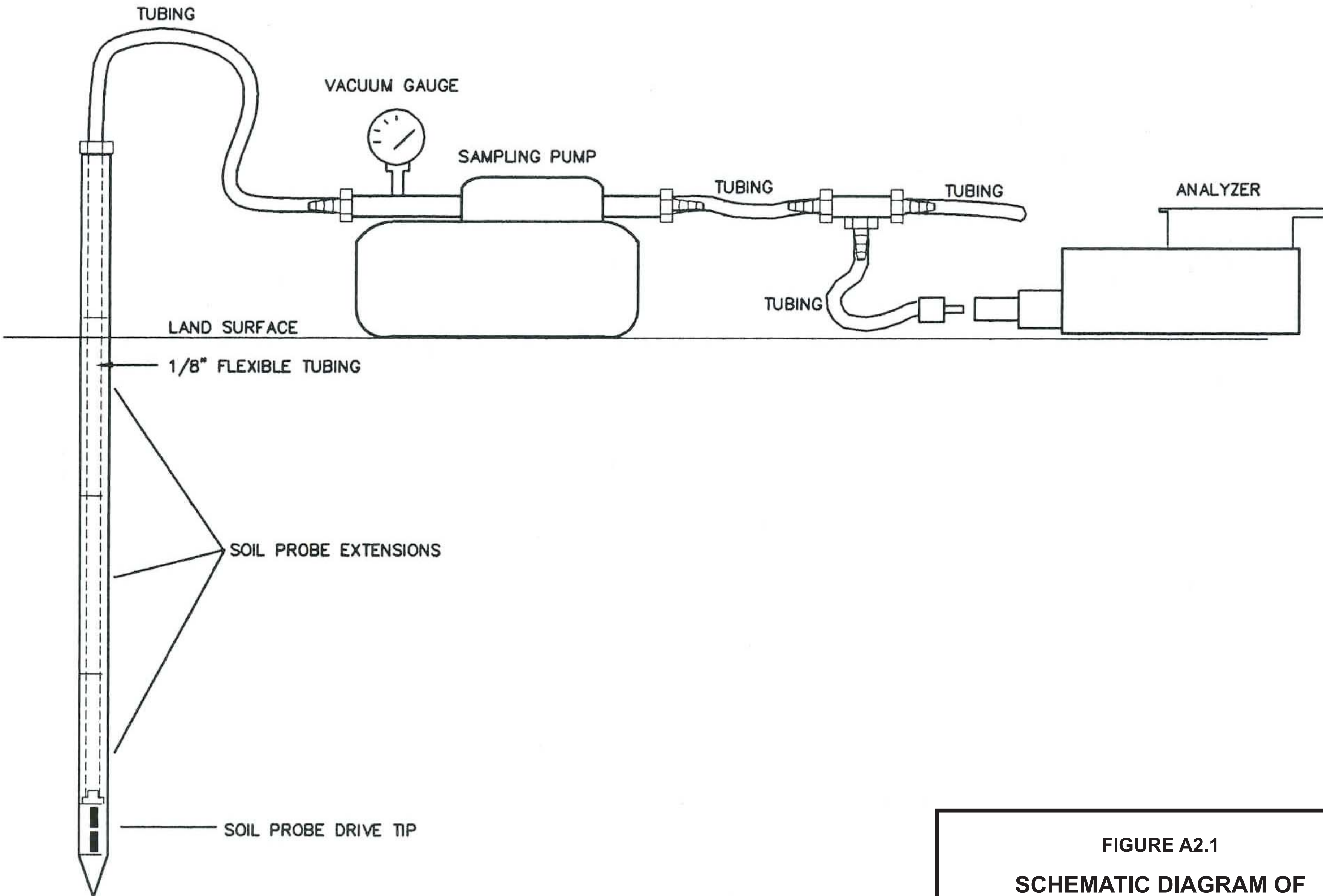

FIGURE A2.1

SCHEMATIC DIAGRAM OF SOIL GAS PROBE AND SAMPLING SYSTEM USING DIRECT METER ANALYSIS

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methane is not excluded from the TVH measurement, TVH 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 while methane passes through to the detector.

A2.3.3 Sampling Pumps

Electric sampling pumps are used both to purge and collect samples from permanent MPs and soil gas probes. The pumps should be either oilless rotary-vane or diaphragm pumps capable of delivering approximately 1 cubic foot per minute (cfm) of air at a maximum vacuum of 270 inches of water. The pumps have oilless filters to eliminate particulates from the air stream.

A2.3.4 Differential Vacuum Gauges

Differential vacuum gauges are used to monitor the vacuum in the sampling point during purging and to estimate the permeability of soil to air flow. Typical vacuum ranges of the gauges are 0 to 50 and 0 to 250 inches of water for sites with sandy and clayey soils, respectively.

A2.4 SOIL GAS SAMPLING PROCEDURES

The following soil gas sampling methods are recommended for extracting and analyzing soil gas samples from either temporary soil gas probes or permanent MPs. Proper sampling procedures will ensure that representative soil gas samples are collected from the subsurface.

A2.4.1 Purging

Purging the soil gas probe or MP is a prerequisite for obtaining representative soil gas samples. A typical purging system (Figure A2.1) will consists of a 1-cfm 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 or MP. 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 MP, the valve or hose clamp is opened and the pump is turned on. Purging is continued until O_2 and CO_2 concentrations stabilize, indicating that purging is complete. Before turning off the pump, the hose clamp or MP valve is closed to prevent fresh air from being drawn into the soil gas probe or MP.

A2.4.2 Soil Gas Sampling -High-Permeability Soils

Sampling methods for high-permeability soils (sand and silt) should be followed if the vacuum measured during purging is less than 10 inches of water. Soil gas sampling and analysis is performed using the same equipment used for purging, minus the vacuum gauge. The sampling pumg is turned on, the sampling point valve or hose clamp is opened, and the extracted soil gas is analyzed for stable $O_2/C0_2$ and TVH concentrations.

A2.4.3 Soil Gas Sampling -Low-Permeability Soils

A different sampling procedure should be followed to collect soil gas samples from low-permeability soils if the vacuum measured during purging is greater than 10 inches of water. The higher vacuums required for sampling increase the risk of vacuum leaks introducing fresh air (oxygen) and diluting the soil gas sample. The introduction of ambient oxygen into bioventing measurements will ruin the bioventing pilot test, leading to false conclusions, and MUST be eliminated.

After purging the sampling point, a soil gas sample is collected in a Tedlar@ bag prior to analysis. The evacuated Tedlar@ bag should be placed inside a desiccator modified for soil gas sample collection. The desiccator is then connected to the sampling point via a hose barb that passes through the desiccator wall. The desiccator is then closed, sealed, and connected to the pump inlet with flexible tubing. The sampling system is shown in Figure A2.2. To collect the sample, the MP valve is opened, the pump is turned on, and the pressure relief port on the desiccator is sealed using either a valve or the sampler's finger. The partial vacuum within the desiccator created by the pump 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. The desiccator is then opened, the Tedlar@ bag valve is closed, and the bag is removed from the desiccator. The soil gas sample is then analyzed by attaching the $O_2/C0_2$ and TVH analyzers directly to the Tedlar@ bag.

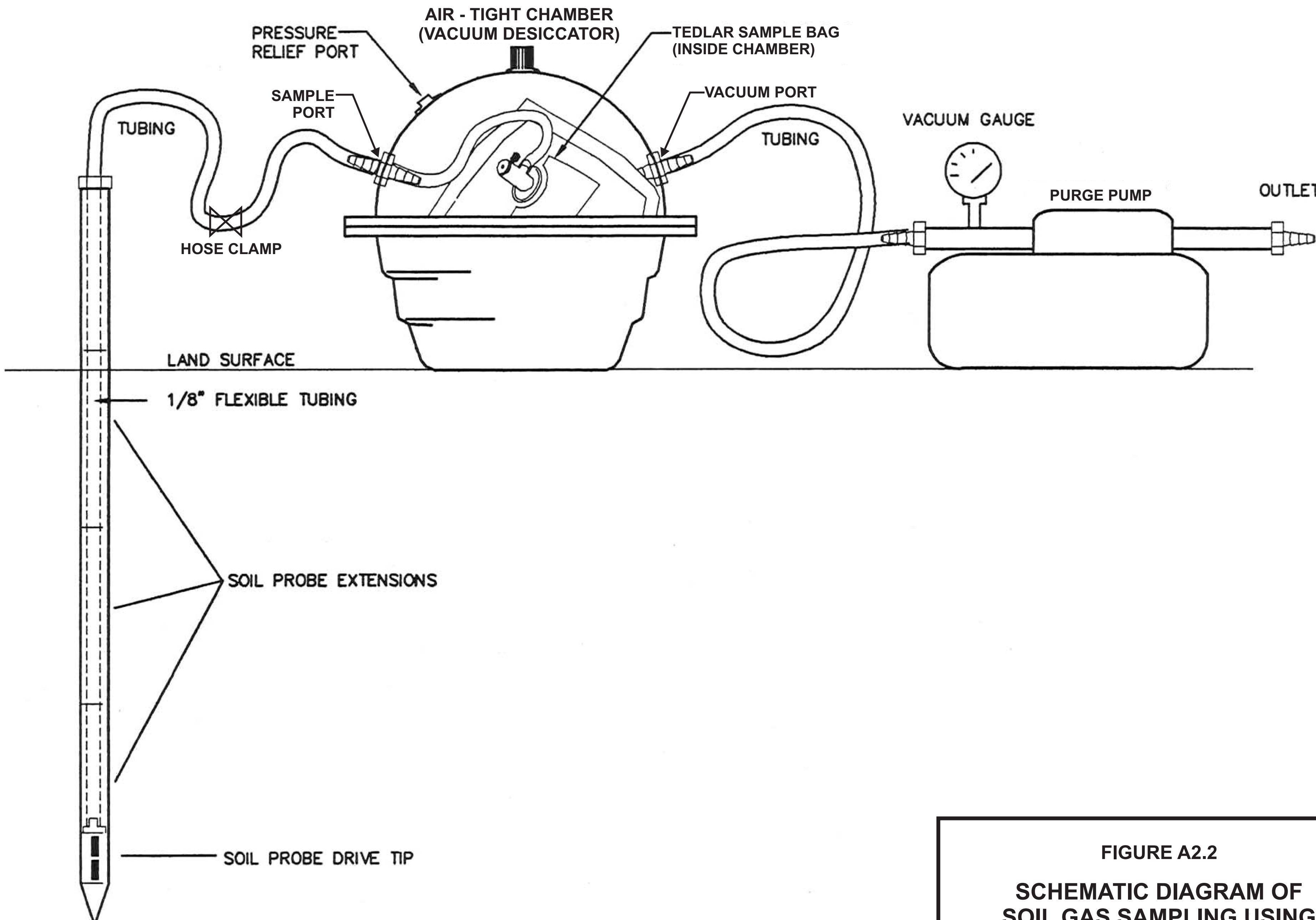

FIGURE A2.2

SCHEMATIC DIAGRAM OF SOIL GAS SAMPLING USING AN AIR-TIGHT CHAMBER

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SECTION A3

INTERPRETATION OF SOIL GAS DATA

The purpose of gathering soil gas data during bioventing investigations is to locate those areas which are most in need of additional oxygen to enhance fuel biodegradation. If a pilot test is to be completed, the area of lowest oxygen concentrations should first be determined. For full-scale applications, it is useful to determine the entire areal extent and depth of soils which exhibit an oxygen deficit (for practical purposes less than 5 percent oxygen). Finally, soil gas data is useful for determining which sites are naturally aerated and therefore do not require mechanical bioventing systems. The following soil gas data sets were collected from six actual candidate sites. The first two sites are typical of anaerobic site conditions which definitely warrant the testing and design of mechanical bioventing systems. The next four sites show how soil gas surveys can be used to determine that remaining contaminants could naturally biodegrade without engineered bioventing enhancements.

A3.1 CANDIDATE SITE 1

- **Site Location/History**: Fire Training Area (FTA-2) at Patrick AFB, FL. The site had been used as a fire training facility for 22 years, and soils are visibly contaminated with JP-4 jet fuel and waste oils.

- **Soil Type(s)**: Sandy soil with shell fragments. Groundwater is approximately 4 feet below the surface.

- **Soil Gas Survey**: A soil gas survey was conducted at the nine locations. An attempt was made to sample soil gas at two depths. Soil gas results are presented in Table A3.1.

- **Interpretation**: High TVH levels remain in these soils, indicating that remaining fuels are not highly weathered and contamination is widespread within the bermed area. 02 at both the 1.5-foot and 2.5-foot sampling depths was completely depleted, indicating that natural diffusion is not meeting the biological oxygen demand of fuel-degrading microorganisms. CO_2 concentrations are also elevated, indicating that this primary biodegradation by-product is also being produced. This is in sharp contrast to background soil gas concentrations in these soils which are at near-atmospheric levels. This site is an excellent candidate for engineered bioventing.

A3.2 CANDIDATE SITE 2

- **Site Location/History**: Building 1813 Underground Storage Tank Leak, Hanscom AFB, MA. Tank containing diesel fuel had leaked. Tank was removed, but an unknown quantity of fuel-contaminated soil remains at the site.

- **Soil Type(s)**: Sandy soil to groundwater, which occurs at 8 to 9 feet.

- **Soil Gas Survey**: A soil gas survey was conducted at the seven locations and at multiple depths. Soil gas results are presented in Table A3.2.

- **Interpretation**: Low levels of TVH indicate that little diesel-contaminated soil remains at the site or that residual fuels are highly weathered. Near-atmospheric O_2 levels at all depths indicate that remaining hydrocarbons are being biodegraded with oxygen supplied by natural diffusion. CO_2 was found at levels above the atmospheric concentration of 0.03 percent, indicating some biological respiration was occurring. Higher CO_2 levels and slightly depressed O_2 levels at PT3 and PT4 indicate remaining fuel is probably located in this area of the site. Natural aeration appears to be providing sufficient 0_2 for biodegradation of remaining fuel residuals.

A3.3 CANDIDATE SITE 3

- **Site Location/History**: Aquasystem Site, Westover AFB, MA. Removal of USTs at this site revealed soil contamination. An unknown quantity of mixed fuels contamination remains in the soil.

- **Soil Type**: Predominantly sand, with groundwater at approximately 13 feet below the surface.

- **Soil Gas Survey**: A soil gas survey consisting of a 12-point grid was completed in and down gradient of the former tank pit. All points were sampled at multiple depths. Results of the survey are provided in Table A3.3

- **Interpretation**: Low levels of TVH 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 percent of O_2 available in this area is more than sufficient to sustain *in-situ* biodegradation. CO_2 ranged from 2 to 8.5 percent 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 impact and potential risk that soil contamination poses to groundwater.

A3.4 CANDIDATE SITE 4

- **Site Location/History**: Oil/water separator leak (CCPOL-l) located near a diesel transfer station at Cape Canaveral AFS, FL.

- **Soil Type(s)**: Sandy soil with shell fragments. Groundwater is approximately 6 feet below the surface.

- **Soil Gas Survey**: 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 A3.4.

- **Interpretation**: Low levels of TVH indicate that little diesel-contaminated soil remains at the site or it is highly weathered. O_2 levels were significantly depleted near SG-2, and generally decreased with depth in points near the oil/water separator. CO_2 levels are elevated in areas with low O_2, 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 in the capillary fringe 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 BTEX compounds could help to determine if the O_2 demand is fuel related.

TABLE A3.1
SOIL GAS SURVEY RESULTS
FIRE TRAINING AREA (FTA-2)
Patrick AFB, FL

LOCATION	Depth (ft)	O_2 (%)	CO_2 (%)	TVH (ppmv)
SG-1	1.5	0.0	9.5	>10,000
	2.5	0.0	9.5	>10,000
SG-2	1.5	1.5	6.5	>10,000
	2.5	0.0	9.5	>10,000
SG-3	1.5	0.0	10.0	>10,000
	2.5	0.0	10.0	>10,000
SG-4	1.5	0.5	7.5	<10,000
	2.5	0.0	9.5	>10,000
SG-5	1.5	0.0	9.5	>10,000
	2.5	0.0	9.5	>10,000
SG-6	1.5	NS	NS	NS
	2.5	0.0	9.0	>10,000
SG-7	1.5	1.5	5.5	>10,000
	2.5	0.0	10.0	>10,000
SG-8	1.5	9.5	9.5	>10,000
	2.5	10.0	10.0	>10,000
SG-9	1.5	9.0	9.0	>10,000
	2.5	9.0	9.0	>10,000

TABLE A3.2
SOIL GAS SURVEY RESULTS
BUILDING 1813 UST
Hanscom AFB, MA

LOCATION	Depth (ft)	O_2 (%)	CO_2 (%)	TVH (ppmv)
PT1	3	20.5	0.8	62
PT2	3	20.5	1.0	60
	6	20.6	0.5	42
PT3	3	19.0	2.0	80
	6	19.0	2.0	78
PT4	3	19.2	2.2	80
	6	19.0	2.4	93
PT6	3	20.5	0.8	46
	6	20.5	0.8	44
PT7	3	20.0	0.5	82
	6	19.8	1.5	61
	7	19.0	1.0	70
PT8	6	19.5	1.5	60
	8	20.5	0.5	48

TABLE A3.3
SOIL GAS SURVEY RESULTS
AQUASYSTEM SITE
WestoverAFB, MA

LOCATION	Depth (ft)	O_2 (%)	CO_2 (%)	TVH (ppmv)
PT1	3	16	3.2	60
	6	12.5	5	60
PT2	3	15.5	4.3	72
	6	13	6	74
PT3	3	18	2.6	74
	6	12	6.2	84
PT4	3	16	4	86
	6	11.5	6	80
PT5	3	14.8	4	76
	6	11	5.2	72
PT7	3	14	7	105
	6	8.5	8.5	69
PT8	3	12	5.5	75
	6	11	6.5	76
PT9	3	11.5	6	90
	6	11	6.2	78
PT11	3	16	3.5	84
	6	15	4	94
PT12	3	18.5	2.5	80
	6	15.5	4.2	91
	9	15	4.8	90
	12	13	5.6	92
PT16	6	17	2	94
	7.5	13	3.5	80
PT17	6	11.8	6.5	92
	9	11	6.5	96
	12	9	8	100

TABLE A3.4
SOIL GAS SURVEY RESULTS
OIL/WATER SEPARATOR (CCPOL-1)
Cape Canaveral AFB, FL

LOCATION	Depth (ft)	O_2 (%)	CO_2 (%)	TVH (ppmv)
SG-1	2.5	15.5	4.0	82
	5.5	12.5	6.0	82
SG-2	2.5	14.0	5.0	76
	5.5	5.5	9.5	77
SG-3	2.5	13.0	5.5	73
	5.5	10.0	7.0	75
SG-4	2.5	19.0	2.0	60
	5.5	18.5	2.5	66
SG-5	2.5	19.5	1.0	57
	5.5	19.0	2.0	60
SG-6	2.5	18.5	2.5	64
	5.5	17.5	3.0	74
SG-7	2.5	20.0	1.0	36
	5.5	20.0	1.0	35
SG-8	2.5	20.5	0.5	34
	5.5	20.2	0.8	43

SECTION A4

USING SOIL GAS DATA FOR BIOVENTING DESIGN

In the absence of very complete, multi-depth soil sampling data, a soil gas survey is essential for the efficient placement of air injection vent wells and permanent soil gas MPs. At sites with deep contamination, more expensive exploratory drilling is required to determine the center and areal extent of contamination.

A4.1 AIR INJECTION WELL DESIGN

In most cases, the optimum location for an air injection well is at the center of contaminant mass, with a screened interval extending over the depth interval of soil contamination. The center of contaminant mass can generally be located by completing a soil gas survey grid, as shown in Section A3, and locating the volume of soil with the lowest oxygen concentrations and highest levels of volatile hydrocarbons. At sites with shallow groundwater, this often corresponds with the capillary fringe where past or present free-phase product has accumulated. At deeper sites, the highest levels of contamination are often found on top of a low-permeability layer in the vicinity of the suspected spill source. The screened interval of the air injection well should be limited to a depth interval with O_2 levels of less than 5 percent. This will focus air flow through the soils with the greatest O_2 demand, and reduce the volume of air injection. One important exception to this design is when the center of contamination is beneath or adjacent a building or underground utility corridor. If high levels of TVH (> 4,000 ppmv) are found in soil gas, air injection can result in undesirable vapor migration into these structures. Under these circumstances, short-term soil vapor extraction may be required to reduce initial high volatile hydrocarbon concentrations.

A4.2 PERMANENT MONITORING POINT DESIGN

Permanent soil gas MPs have two primary functions in bioventing applications: measuring the rate of 0_2 utilization to determine approximate rates of biodegradation, and monitoring the pressure and movement of soil gases in the treatment area. Because the rate of O_2 utilization is most accurately measured in the most anaerobic soil volume, data from the soil gas survey can be used to place several soil gas points in the most O_2-depleted soil volume.

For bioventing pilot tests it is also important to locate at least one multi-depth soil gas point at the outer limit of contamination or outer limit of expected O_2 influence from the single air injection well. In a properly completed soil gas grid, the outer limit of contamination can often be estimated both by a noticeable reduction in TVH concentrations and an increase in O_2 levels. The depth interval of perimeter MPs should be the same as MPs located in contaminated soils to monitor oxygen influence at critical depths.

A4.3 SUMMARY

Data on soil gas concentrations of O_2/CO_2 and TVH can provide valuable insight into the extent of subsurface contamination and the potential for *in-situ* bioventing. The procedures outlined in this appendix are intended to 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.

SECTION A5

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APPENDIX B

SUGGESTED TEST PLAN OUTLINE

SUGGESTED TEST PLAN OUTLINE

The following outline has been successfully used at hundreds of bioventing pilot test sites and is a suggested starting point for your test plan.

Section 1 - Introduction

1.1 – Purpose of Plan
1.2 - Description of Bioventing
1.3 - Objectives of Test
1.4 – Base Support Requirements

Section 2 - Site Description

2.1 – Site History
2.2 – Nature and Extent of Soil Contaminants
2.3 - Site Geology and Hydrogeology
2.4 - Utilities and Surface Features
(Include simple map of utilities in the test site area)

Section 3 – Pilot Test Description

3.1 - Test Well Layout

3.2 – Test Equipment and Calibration
3.3 - Test Procedures (Recommend that you reference this document or include it as an appendix)
3.4 - Sampling Procedures (Reference an existing Sampling and Analysis Plan if soil samples are collected)
3.5 - Post-Test Site Restoration/Demobilization

Section 4 – Post-Test Reporting

4.1 – Data Analysis (Note ERPIMS does not apply to test data)
4.2 – Test Results and Full-Scale Design Parameters (what will be reported after the test)

Section 5 – Test Schedule

Section 6 – Key Points-of-Contact

Section 7 – References

Appendices - This document can be included as an appendix or referenced.

Existing soil boring logs, soil contamination data, groundwater elevations, are all helpful to include in an appendix.

APPENDIX C

PILOT TESTING DATA LOGS

FORM 1
BASELINE SOIL GAS MONITORING

SITE:_________________________________ O_2/CO_2 Meter Calibrated? Yes__ No__

PERSON SAMPLING:___________________ TVH Meter Calibrated? Yes__ No__

Monitoring Point (MP)	Date	Time	Purge Vacuum (inches H_2O)	Oxygen (%)	Carbon Dioxide (%)	TVH (ppmv)	Comments

FORM 2
OXYGEN/PRESSURE INFLUENCE TEST

SITE: ________________________________ **O_2/CO_2 Meter Calibrated? Yes__ No__**

PERSON SAMPLING: __________________ **TVH Meter Calibrated? Yes__ No__**

SYSTEM TURN ON DATE:_______________ **TIME:__________**

Monitoring Point (MP)	Date	Time	Purge Vacuum (inches H_2O)	Oxygen (%)	Carbon Dioxide (%)	TVH (ppmv)	Comments
Monitoring Point (MP)							
Monitoring Point (MP)							

FORM 3
IN-SITU RESPIRATION TEST

SITE: ___________________________________ **O_2/CO_2 Meter Calibrated? Yes__ No__**

PERSON SAMPLING: ___________________ **TVH Meter Calibrated? Yes__ No__**

SYSTEM TURN ON DATE:_______________ **TIME:__________**

Date	Time	Oxygen (%)	Carbon Dioxide (%)	TVH (ppmv)	Purge Vacuum (inches H_2O)	Comments