NAVAL FACILITIES ENGINEERING SERVICE CENTER
Port Hueneme, California 93043-4370

Technical Memorandum
TM-2186-ENV

TECHNICAL REQUIREMENTS TO CONSIDER WHEN PREPARING A SCOPE OF WORK FOR FULL-SCALE IMPLEMENTATION OF BIOVENTING

May 1996

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ABSTRACT

This document summarizes technical information needed to prepare a Scope of Work (SOW) to implement full-scale bioventing and for reviewing the contractor submittals received in response to the SOW. The guidance document describes information needed to specify the materials, methods, and performance requirements for an effective field implementation of bioventing. The document starts by tabulating the data required to support preparing an effective SOW. This document discusses all phases of full-scale implementation of bioventing, including

- design
- installation
- operation
- maintenance
- closeout.

The SOW preparation guide provides an approach for use by Navy facilities personnel when preparing contract delivery orders for full-scale bioventing implementation. The description of the minimum required features of a bioventing system is supplemented by information about possible options to give the facilities personnel the flexibility to develop SOWs that best respond to site-specific requirements. The guide is intended to foster timely, concise, and systematic preparation of SOWs used to obtain services to plan and implement bioventing.

TECHNICAL REQUIREMENTS TO CONSIDER WHEN PREPARING A SCOPE OF WORK FOR FULL-SCALE IMPLEMENTATION OF BIOVENTING

8 May 1996

Section 1: INTRODUCTION

This document gives guidance for preparing a Scope of Work (SOW) to implement full-scale bioventing at a petroleum-contaminated site and for reviewing the contractor submittals received in response to the SOW. The guidance describes information needed to specify the materials, methods, and performance requirements for an effective field implementation of bioventing. The information provided is grouped into three general categories as follows:

- site data required to design and install a bioventing system
- essential and optional design and installation features for a successful bioventing remediation system
- essential and optional operating, maintenance, and closeout activities required to verify effective operation of the bioventing system.

The SOW preparation guide provides an approach for use by Navy facilities personnel when preparing contract delivery orders for full-scale bioventing implementation. Technical details specific to bioventing are described in the main text. A generic SOW for corrective measure implementation is provided in Appendix A based on information provided by the U.S. Environmental Protection Agency (U.S. EPA) (U.S. EPA, 1986b). The U.S. EPA provides additional guidance on the content of a SOW to retain remedial action services in two other documents (U.S. EPA, 1986a; U.S. EPA, 1988). The Navy personnel responsible for SOW preparation can combine bioventing technical requirements in the main body of this guide with general provisions in their organization's standard SOW format or in the generic SOW in Appendix A to quickly prepare a SOW applicable to their specific needs and conditions. The guide is intended to foster timely, concise, and systematic preparation of SOWs used to obtain services to plan and implement bioventing.

The SOW guide provides more prescriptive direction about ways to implement bioventing than may be desired in the SOW. Typically, a SOW should define what must be done while leaving as much flexibility as possible. The SOW guide provides information on the material, functional, and performance requirements but also, where applicable, describes the most commonly accepted implementation. The writer may elect to omit specific information on how the work is usually done. The "how to" information may be used instead to develop evaluation criteria for reviewing responses to the SOW. For example, the two checklists in Section 5.0 would not be included in a typical SOW but may be useful in evaluating the responses to the SOW or the deliverables prepared under the SOW.

Example vendors or equipment items are mentioned in some sections of this SOW preparation guide. The examples are intended to help clarify principles and practices of bioventing by indicating some specific implementations, but many approaches are possible. Mention of a vendor or an item does not constitute a recommendation or endorsement.

Section 2: TECHNOLOGY OVERVIEW

In bioventing processes, a system of vent wells is used to inject (or occasionally extract) air to aerate contaminated soil in the unsaturated zone. The general arrangement of a bioventing system is shown in Figure 1. Bioventing relies on the ability to move air through the contaminated soil formation. Airflow increases the availability of oxygen and promotes aerobic biodegradation of organic compounds. The organics are oxidized to their basic inorganic constituents (mineralization). The soil moisture content, temperature, or other factors may be adjusted to improve the biodegradation process.

Moving air to supply oxygen has significant advantages over supplying oxygen in air-saturated water to stimulate in situ bioremediation. The solubility of oxygen in water is less than 10 mg/L, so large amounts of water are required to sustain in situ biological action. The hydraulic conductivity of soil limits the ability to infiltrate the required flow of water. Furthermore, bioventing is not expected to increase the migration of contaminants to groundwater as may happen when air-saturated water is used to promote biodegradation. Bioventing is, therefore, applicable to sites where soil permeability or the potential for contaminant migration makes the site unsuitable for bioremediation with oxygen-saturated water. Terms used to describe bioventing principles and implementation are defined in a glossary provided as Appendix B.

Bioventing typically is applied in situ to the unsaturated zone and is applicable to any organic contaminant that can be aerobically biodegraded, but to date has been implemented primarily at petroleum-contaminated sites. Bioventing is not applicable to chlorinated hydrocarbons. Much of the hydrocarbon residue at a fuel-contaminated site is found in the unsaturated zone soils, in the capillary fringe, and immediately below the water table (Figure 2). Seasonal water-table fluctuations can spread residues in the area immediately above and below the water table (smear zone). Conventional groundwater treatment involves pump-and-treat systems where groundwater is pumped, treated, and either discharged or reinjected. Pump-and-treat methods can prevent continued migration of contaminants, but rarely achieve cleanup goals. Bioventing systems are designed to remove the contaminant source from the unsaturated zone, thereby preventing future or continued contamination of the groundwater. Bioventing does not, however, treat the groundwater itself.

The objective of bioventing system design and implementation is to aerate the contaminated soils while causing little or no volatilization of contaminants. The injection of air in bioventing minimizes volatilization and optimizes biodegradation. Aeration may be accomplished through air injection (see Section 4.1.1) or air injection supplemented with soil gas extraction (see Section 4.1.2). Unlike bioventing, soil vapor extraction (SVE) systems are designed to create significant soil gas advection to remove contaminants by volatilization. As a result, bioventing typically uses much lower airflow rates and usually does not involve air extraction.

Although bioventing and soil vapor extraction (SVE) use similar equipment, fundamental differences between the options must be recognized and understood. It is essential to understand that bioventing is not just SVE operated at a low airflow rate. SVE applies a vacuum to extract soil gas, whereas bioventing almost always applies pressure to create an expanded bioreactor around the well. An SVE system is designed to be operated at high airflow rates to maximize the volatilization of low-molecular-weight organic compounds. Although some biodegradation does occur during the process, the primary removal mechanism is through the stripping action of the extracted air. In contrast, the objective of bioventing is to promote degradation of the contaminants in situ. Therefore, bioventing

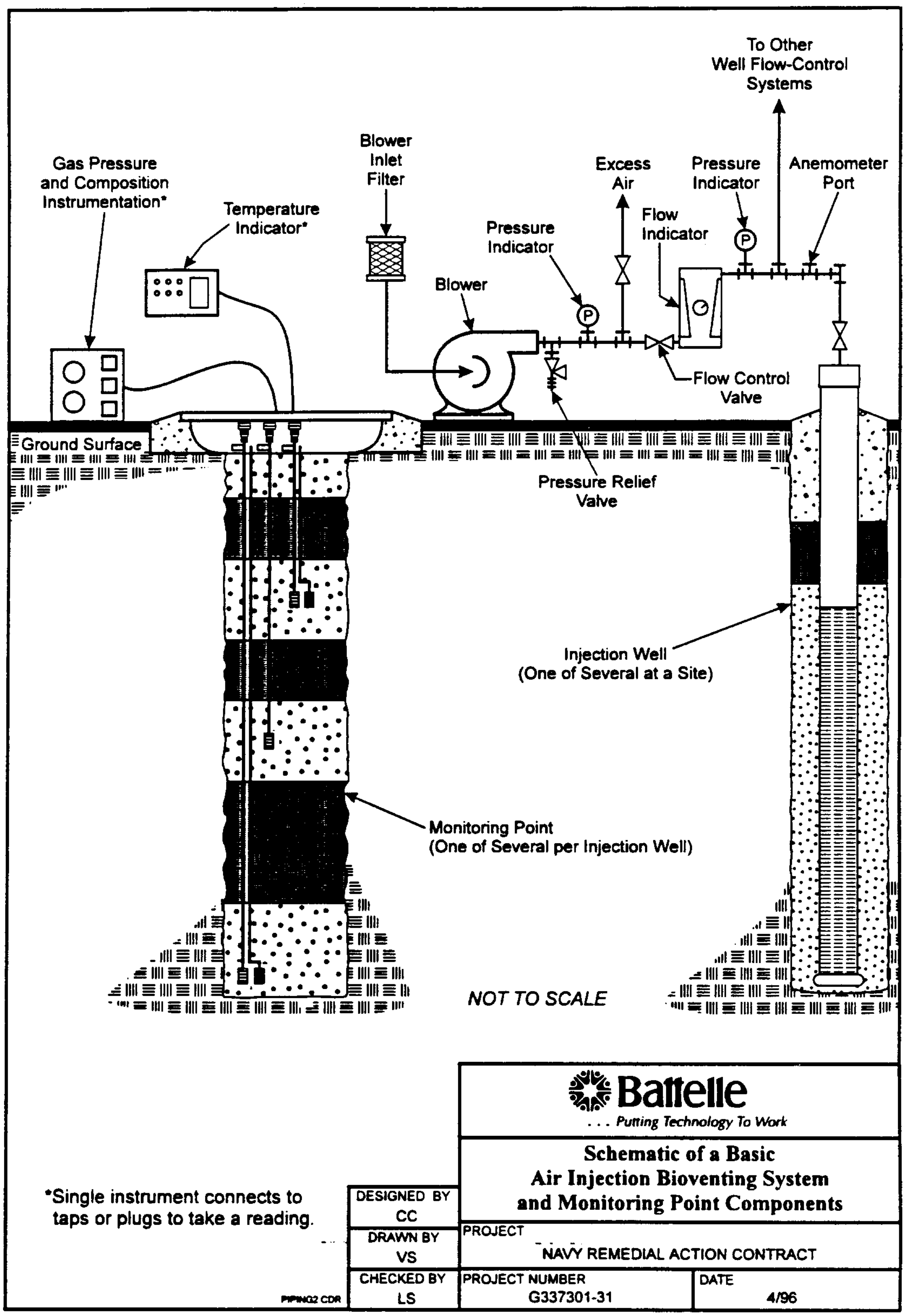
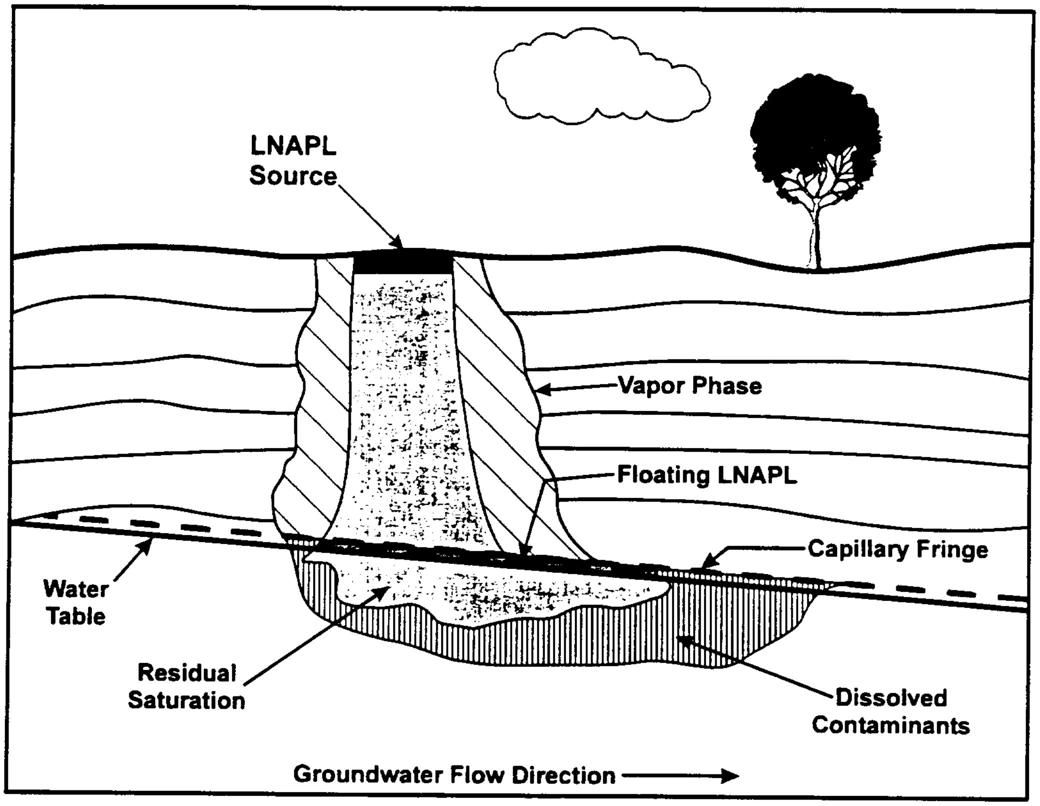


Figure 1. Schematic of a Basic Air Injection Bioventing System and Monitoring Point Components.



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DESIGNED BY AL	Contaminant Distribution at a Typical Hydrocarbon-Contaminated Site	
DRAWN BY VS	PROJECT NAVY REMEDIAL ACTION CONTRACT	
CHECKED BY LS	PROJECT NUMBER G337301-31	DATE 3/96

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Figure 2. Contaminant Distribution at a Typical Hydrocarbon-Contaminated Site.

systems are designed to inject air at lower flow rates to minimize volatilization while providing enough oxygen to maximize biodegradation of aerobically biodegradable compounds.

Section 3: KEY ELEMENTS IN SELECTION OF BIOVENTING

This section describes the types of information that are used to prepare a SOW.

3.1 Required Design Data. Tables 1, 2, and 3 summarize the soil, site, and contaminant information that must be available prior to writing the SOW. All the listed data must be organized in a format that can be provided to the prospective service providers. The typical format for organizing and presenting the information is a remedial investigation/feasibility study (RI/FS) report, or equivalent. Tables 1, 2, and 3 indicate why each data item is needed to design and implement a full-scale bioventing system. Application of the required design data to the evaluation and selection of bioventing is illustrated in Figure 3. Figure 3 specifies numeric conditions that favor or inhibit bioventing application.

3.2 Applicable Documents. This section lists documents that assist in the design, installation, operation, and maintenance of bioventing systems. Prospective bidders should have these documents and be familiar with their application. As discussed in Section 2.0, SVE systems and bioventing systems use some of the same types of equipment, so several of the documents containing information applicable to design, installation, operation, and maintenance of bioventing systems discuss SVE and bioventing in combination or SVE alone.

1. U.S. Air Force, *Test Plan and Technical Protocol for a Field Treatability Test for Bioventing*. AFCEE, May 1992.

2. U.S. Air Force and U.S. Environmental Protection Agency. *Principles and Practices of Bioventing Volumes I and II.* September, 1995.

Table 1. Minimum Required Soil Data to Support Bioventing Implementation[a]

Data Item	Purpose and Comments
In situ respiration test results	In situ respiration testing measures biological activity Oxygen use rate is one method for estimating radius of influence
Soil type and stratigraphy	High clay content reduces soil permeability
Soil moisture content	Lack of moisture may reduce biological activity High moisture content reduces soil permeability
Soil permeability	Soil permeability or well radius of influence must be known to allow design of the bioventing system

(a) See Figure 3 for specific guidance on how these data affect the effectiveness and implementability of bioventing.

Table 2. Minimum Required Site Data to Support Bioventing Implementation[a]

Data Item	Purpose and Comments
Required cleanup goals	Meeting the required cleanup goals is the most fundamental measure of bioventing system effectiveness
Historical water-table level and degree of periodic fluctuations	Bioventing is not effective in the saturated zone Water level fluctuations smear contaminants vertically
Potential for continuing contaminant sources	It is difficult to implement or assess the effectiveness of bioventing if contaminants continue to enter the environment Presence of other sources is indicated when groundwater contamination persists after soils are remediated.
Location of surface features	Location of surface seals such as paved areas must be known to allow design of well locations
Location of subsurface features	Location of subsurface features that can block airflow must be known to allow design of well locations Subsurface volumes such as pipe runs or basements may require installation and operation of air extraction wells to prevent vapor accumulation in the volume
Site rainfall	Arid sites may require provisions for addition of soil moisture
Site temperature history	Extreme cold weather sites may require provisions for surface insulation or soil warming
Voltage and amperage of available power supply	Power supply characteristics determine blower motor selection If not available, consider solar-powered or passive bioventing system

(a) See Figure 3 for specific guidance on how these data affect the effectiveness and implementability of bioventing.

3. U.S. Army Corps of Engineers. EM 1110-1-4001, *Soil Vapor Extraction and Bioventing*. November 1995.

4. U.S. Environmental Protection Agency. Office of Solid Waste and Emergency Response (OSWER) Directive 9355.0-4A, *Superfund Remedial Design and Remedial Action Guidance*. June 1986.

5. U.S. Environmental Protection Agency. Office of Solid Waste and Emergency Response (OSWER) Directive 9902.3, *Interim Final Corrective Action Plan*. November 1986.

Table 3. **Minimum Required Contaminant Data to Support Bioventing Implementation**[a]

Data Item	Purpose and Comments
Soil gas composition (O_2, CO_2, and TPH)	Low O_2 and high CO_2 in contaminated areas indicate natural biological degradation may be taking place. Bioventing aeration wells should be located in contaminated areas where the O_2 concentration indicates biodegradation is oxygen-limited.
Type of contaminants	Contaminant type helps determine biodegradation potential.
Concentration of contaminants	High contaminant concentrations may be toxic to microorganisms.
Contaminant distribution	Contaminated volume is a major factor in determining required bioventing air flow. Contaminant location must be known to allow design of well location.
Free product distribution (if present)	Free product removal may be appropriate prior to bioventing implementation or as part of bioventing implementation [vacuum-enhanced free product removal (bioslurping)].
Contaminant vapor pressure/contaminant boiling range/contaminant Henry's law constant	Volatile contaminants may vaporize rather than biodegrade. If air extraction wells are needed, the presence of volatile contaminants may require off-gas treatment.

(a) See Figure 3 for specific guidance on how these data affect the effectiveness and implementability of bioventing.

6. U.S. Environmental Protection Agency. EPA/600/8-91/006, *Preparation Aids for the Development of Category II Quality Assurance Project Plans*. February 1991.

7. U.S. Environmental Protection Agency. EPA/540/G-89/004, *Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA*. October 1988.

8. U.S. Environmental Protection Agency. EPA/540/G-89/006, *CERCLA Compliance with Other Laws, Part 1*. August 1988.

9. U.S. Environmental Protection Agency. EPA/540/G-89/006, *CERCLA Compliance with Other Laws, Part 2*. August 1989.

10. U.S. Environmental Protection Agency. EPA/540/2-91/003, *Soil Vapor Extraction Technology - Reference Handbook*. February 1991.

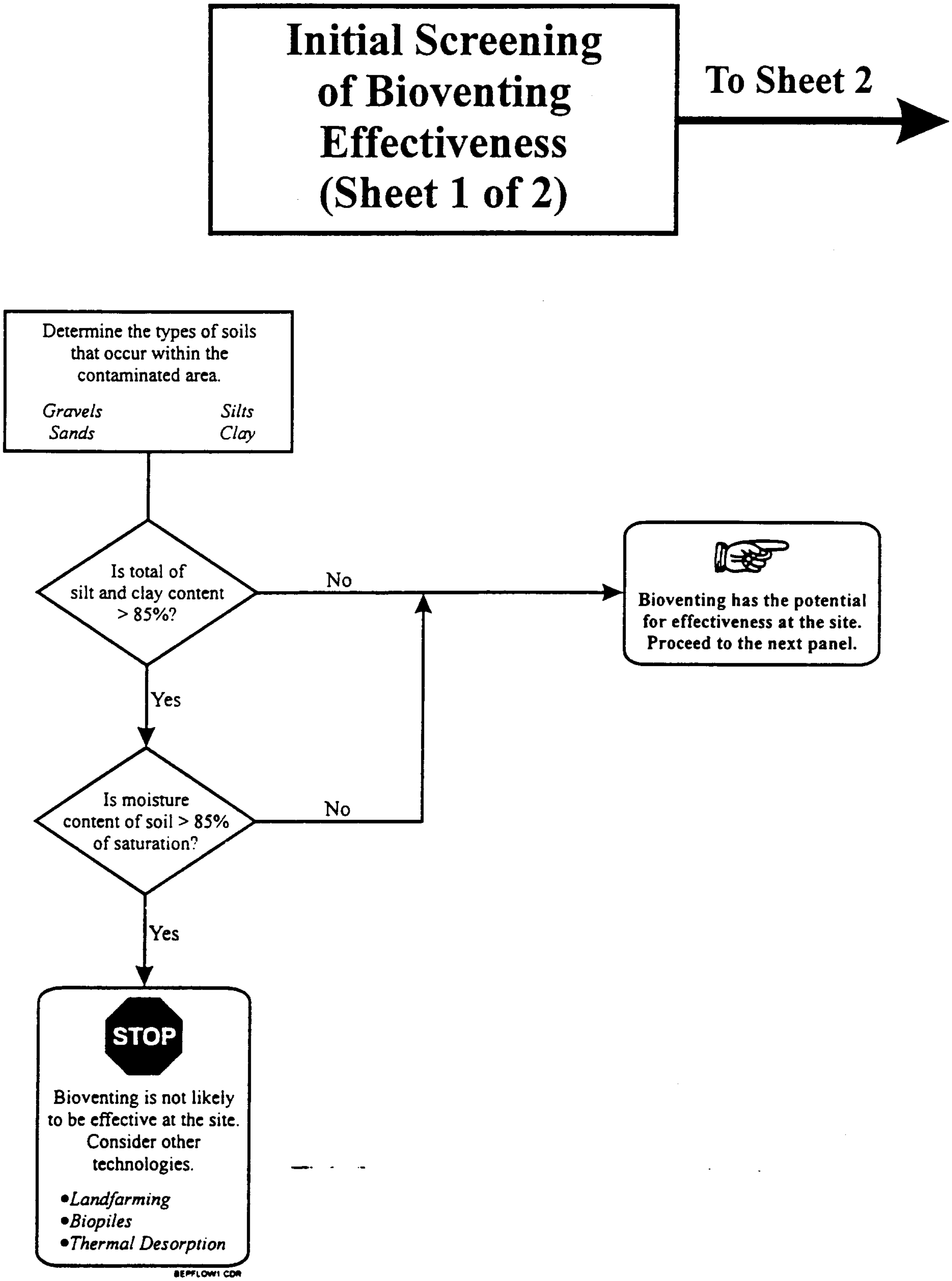


Figure 3. Bioventing Evaluation Process Flowchart.

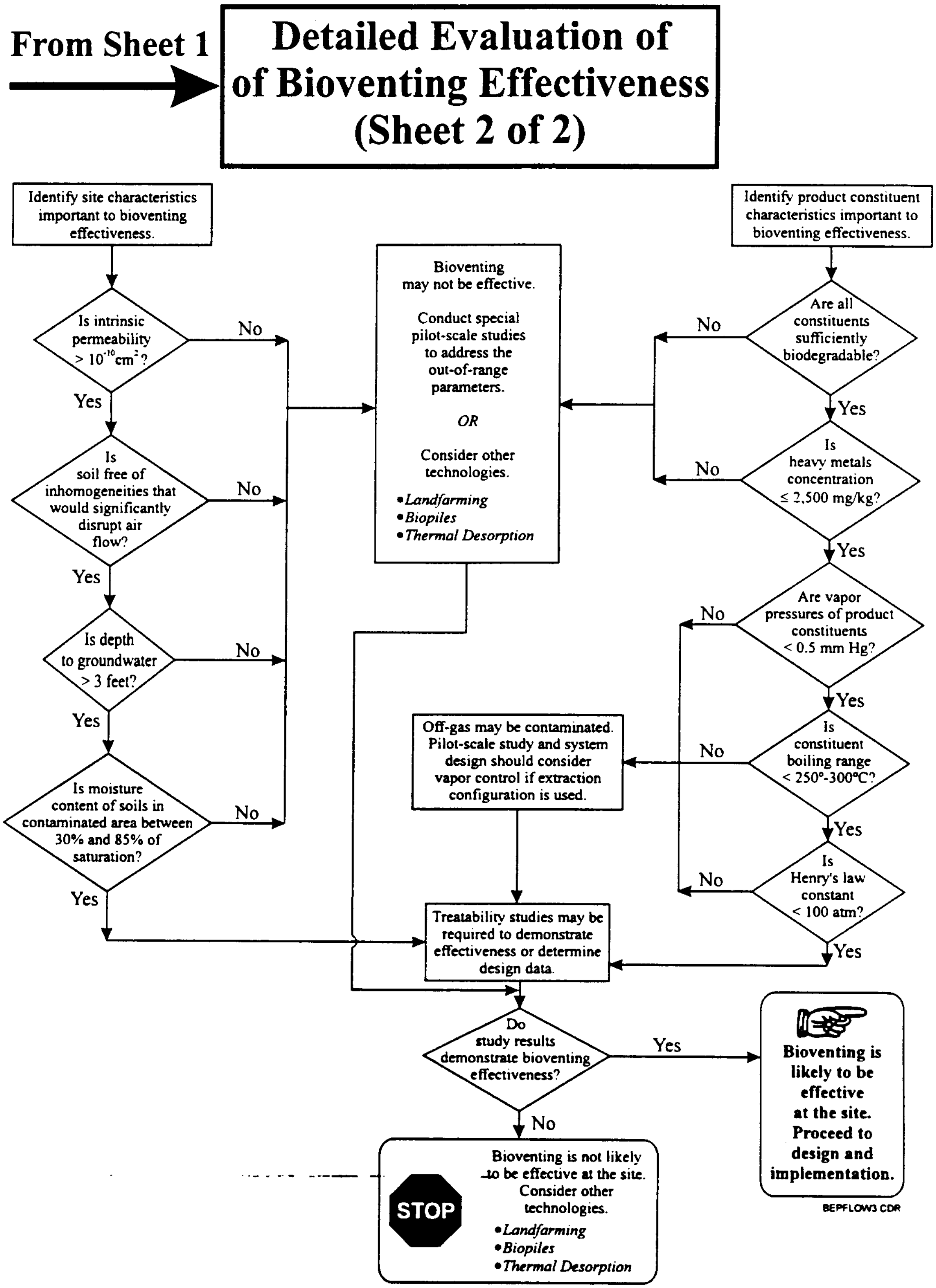


Figure 3. Bioventing Evaluation Process Flowchart (continued).

11. U.S. Environmental Protection Agency. EPA/540/2-91/013A, *Guide for Conducting Remedial Treatability Studies Under CERCLA: Aerobic Biodegradation Remedy Selection*. July 1991.

12. U.S. Environmental Protection Agency. EPA/540/R-92/071a, *Guide for Treatability Studies Under CERCLA*. October 1992.

13. U.S. Environmental Protection Agency. EPA/540/S-94/500, *Engineering Forum Issue - Considerations in Deciding to Treat Contaminated Unsaturated Soils In Situ*. December 1993.

14. U.S. Environmental Protection Agency. EPA/600/R-93/124, *In Situ Bioremediation of Groundwater and Geological Material: A Review of Technologies*. September 1993.

Section 4: BIOVENTING DESIGN AND INSTALLATION STRATEGY

This section describes the features required for design and installation of a full-scale bioventing system and outlines optional features that may be needed in special circumstances.

4.1 Design Requirements. The design of a bioventing system is based on the results of site characterization and treatability testing results listed in Section 3.0. Methods to collect the required data are described in U.S. Air Force (1992) and U.S. Air Force and U.S. Environmental Protection Agency (1995).

4.1.1 Minimum Required Design Features. The basic steps involved in designing a bioventing system are described in this section as follows:

(a) Determine required airflow configuration (injection, extraction, or both)
(b) Determine required airflow rate for the site
(c) Determine well arrangement
(d) Determine system pressure loss
(e) Select blower
(f) Design vent wells and piping
(g) Determine monitoring point locations and design.

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

Air injection involves the introduction of air under pressure into the contaminated zone. Some volatile contaminants migrate with the air into surrounding soil where they biodegrade. Given adequate oxygen supply, the volatilized hydrocarbons will biodegrade in the surrounding uncontaminated soils, increasing the fraction of contaminants biodegraded compared to the fraction biodegraded in an air extraction configuration.

In addition to creating an expanded bioreactor, air injection into the unsaturated zone increases the air pressure around the well, which lowers the water table and exposes some contaminated soil in the capillary fringe to bioremediation. Exposing the capillary fringe to aeration has important implications. At many sites, the capillary fringe is highly contaminated, and the capillary fringe is aerated and more effectively bioremediated when the water table is lowered. In addition, the dewatering effect frequently increases soil gas permeability, resulting in an increased radius of influence.

A schematic diagram of a basic air injection system is presented in Figure 1. The system is relatively simple, involving a blower, an air distribution system, instrumentation, vent wells, and monitoring points. A properly designed and operated bioventing system operating in the injection configuration will not release significant air emissions and does not require aboveground vapor treatment, U.S. Air Force and U.S. EPA (1995)

At some sites, soil gas extraction wells may be needed to supplement air injection wells. For example, whenever the radius of influence of a vent well reaches basements, utility corridors, or surface structures, an air extraction system will reduce the risk of moving gases into these areas.

This precaution will prevent the accumulation of explosive or toxic vapors in these structures. The air extraction design option is discussed in Section 4.1.2.

4.1.1.2 Determine Required Airflow Rate for the Site. The bioventing system must be designed to supply sufficient airflow to aerate the contaminated volume. Data from numerous sites contaminated with various types and mixtures of contaminants have shown that microbial activity is not oxygen-limited when the soil gas oxygen concentration is over about 1 to 2%. To ensure adequate oxygen levels throughout the in situ treatment volume, the bioventing system should be designed to provide a minimum soil gas oxygen concentration of 5% (U.S. Air Force and U.S. Environmental Protection Agency, 1995).

The flowrate required for the bioventing system can be estimated from the oxygen demand of the indigenous microorganisms. The required air is best determined from the maximum oxygen use rate measured by in situ respiration testing. Equation (1) can be used to estimate the required airflow rate.

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

where:

Q_s	=	air input flowrate for the site (ft^3/min)
$20.9\% - 5\%$	=	change in oxygen concentration (%)
k_o	=	oxygen use rate (%/hr)
V	=	volume of contaminated soil (ft^3) where biodegradation is oxygen-limited
θ_a	=	gas-filled porosity (fraction, typical range 0.2 to 0.3)

As a rough check of the calculation, the air input flowrate for the site can be estimated as the flowrate needed to displace the soil's pore volume ($V\theta_a$) one time per day. This rough estimate is based on assumptions of plug flow and an oxygen use rate of 0.6625%/hr.

The design airflow rate should be at least 40% greater than the flowrate determined from equation 1 to allow for inefficient air distribution and for adjusting the airflow balance to each vent well during bioventing system startup (see Section 5.1.1).

4.1.1.3 Determine Well Arrangement. The number and location of vent wells must be determined so as to provide uniform aeration of the contaminated volume. The well spacing, and thus the required number of wells, is determined from the well radius of influence (R_I). The R_I may be estimated by any of three methods as follows:

- measuring pressure in monitoring points during a soil gas permeability test
- using the airflow into a well and measured oxygen consumption data
- measuring empirically.

R_I can be estimated using pressure measurements taken during an in situ permeability test. Using pressure measurements alone is a common approach in soil venting or SVE design and is the fastest and easiest method to estimate the R_I. The R_I is estimated by measuring in situ pressure in monitoring points during air injection. The log of the pressures is plotted as a function of distance radially out from the injection well. The R_I is the maximum distance where the pressure rise due to injection remains above a prespecified level. Using a prespecified level of 0.1"H_2O (25 Pa) for the measured change of in situ pressure rise will give an estimated R_I that is conservative for well spacing and site aeration. The process for taking the pressure measurements and using them to estimate the R_I is described in more detail in U.S. Air Force and U.S. Environmental Protection Agency (1995).

Determining R_I by pressure measurement alone limits accuracy because pressure change is only one of three factors that affect the R_I for the bioventing process. The airflow rate and the oxygen consumption rate are the other two factors that should be considered. In low-permeability soils, a pressure effect may be seen in a monitoring point, but airflow rates to that point may be too low to supply adequate oxygen. Conversely, in a high-permeability soil, airflow rates sufficient to supply oxygen may occur even when the pressure differential is too small to measure.

Accounting for the airflow and oxygen consumption rate involves an iterative process to determine the appropriate well spacing. The pressure change method is used to give the initial estimate of the R_I. The number of wells needed is determined based on the wells needed to uniformly cover the contaminated area with a spacing between well centers equal to 1.4 to 2 times the R_I. The airflow rate per well (Q_w) is then determined by dividing the total airflow rate (Q_s from equation 1) by the estimated number of wells. Using Q_w and the measured oxygen use rate for the site in equation 2 gives an estimate of the R_I based on oxygen supply and use. Assuming the vent well is installed vertically so that airflow can be described in cylindrical coordinates, and assuming that the R_I is much greater than the well borehole radius, equation 2 can be used to calculate R_I.

$$R_I = \sqrt{\frac{Q_w(20.9\% - 5\%)(60\ \text{min/hr})}{\pi\ h\ k_o \theta_a}} \qquad (2)$$

where:

R_I	=	radius of influence (ft)
Q_w	=	airflow rate per well (ft^3/min)
20.9% − 5%	=	change in oxygen concentration (%)
k_o	=	oxygen use rate (%/hr)
θ_a	=	air-filled porosity (cm^3_{air}/cm^3_{soil})
h	=	aerated thickness (ft)

The number of wells or the airflow rate may need to be increased based on consideration of the R_I measured by pressure changes and the R_I calculated from equation 2. The combination accounts for all three of the key factors influencing air distribution from the well: pressure connection, air supply, and oxygen use. Judgment and experience are needed to select the R_I, but some general guidance can be given. In the simplest case the calculation of R_I from equation 2 will be within 25% of the R_I determined from pressure measurement, and no adjustment is needed. If the R_I from equation 2 is larger than the R_I based on pressure change, again no adjustment is needed. If the R_I from equation 2 is smaller than the R_I based on pressure change, the design airflow to the contaminated volume should be increased. The air supply may be increased either by adding enough wells with airflow Q_w to cover the contaminated area or by increasing the airflow to raise the R_I calculated from equation 2 to equal the R_I based on pressure measurement.

A site-specific pilot test gives the most conclusive determination of R_I. A pilot test requires installing a well, a blower, and monitoring points. The blower is operated at an airflow rate estimated from the site oxygen demand and the R_I determined from pressure measurements. The O_2 and CO_2 concentrations are then measured in monitoring points to determine the R_I .

Pilot testing is not warranted in many cases. Pilot-scale testing is expensive, because a complete bioventing system must be installed and operated until steady state is reached before performing the test. At a minimum, several days of operation are required to reach steady state and, at some sites, more than 30 days are required. At many sites, the increased accuracy in determining well spacing will not reduce costs sufficiently to offset the cost of the pilot test. Pilot testing is most likely to provide positive cost benefits for sites with difficult geologic or contaminant conditions (see Figure 3) or with a large volume of contaminants.

Once the number of wells is established, the well arrangement should be finalized. If one well can provide sufficient airflow and R_I to remediate the contamination, the well usually should be placed in the geometric center of the contamination. Rare site-specific factors, such as known preferential flow pathways, might lead to an off-center placement to allow faster site remediation.

When more than one well is used, it is important to consider the effect that each well has on the in situ airflow from the other wells. In theory, volumes of stagnant air can develop at points equidistant from several wells. However, given vertical and horizontal flow paths and diffusion, these stagnant areas are unlikely to occur in practice.

4.1.1.4 Determine System Pressure Loss. The pressure loss in the piping manifold and vent well must be overcome to supply the required airflow for the bioventing system. System pressure drop is the sum of two components:

- the pressure drop in the system piping
- the pressure in the vent wells (in an air injection configuration) or the vacuum in the vent wells (in an extraction configuration due to flow resistance in the well and soil).

Pressure loss in the manifold piping can be determined using standard approaches for calculating the frictional losses due to air flowing through pipes and valves. Methods for calculating frictional losses are detailed in USACE (1995). Unfortunately, the pressure loss in the vent well is a major contributor to the total pressure loss and is more difficult to quantify. The most accurate approach is to conduct a pilot test to measure the pressure as a function of flowrate in a vent well with a similar size and design as is planned for the full-scale system. As stated above, pilot testing requires a significant expenditure. Lacking pilot test data, the well pressure loss can be estimated using prior experience at similar sites supplemented with methods published in the literature (Johnson et al., 1991). Using an estimate of the vent well pressure drop increases the uncertainty and may result in selection of an oversized blower. The increment in the cost of the blower usually will be less than the cost of the pilot test, so the cost to perform field testing to reduce uncertainty about the magnitude of the pressure loss may not be warranted. Excess airflow produced by an oversized blower can be discharged through a bypass valve located in the blower outlet piping.

Bioventing uses low airflow rates so, in practice, the pressure in a well should never be limiting. However, it is good practice to check the pressure required in the well relative to the length of the well seal (see Section 4.1.1.6) to ensure that the vent well pressure does not exceed the well seal capabilities. In the unlikely event that the well pressure is too high, the number of wells should be increased and the airflow per well decreased in direct proportion.

4.1.1.5 Select Blower. A blower is required to provide the driving force to move air through the bioventing system. In selecting the blower size, one must consider the required airflow rate and the total system pressure drop. Centrifugal regenerative blowers are the most commonly used types of blowers for bioventing systems. Other blower options are discussed in Section 4.1.2.

Proper sizing and selection of a blower ensures that the unit can deliver the required airflow at the necessary pressure and that it operates properly. The blower should be selected by comparing the system airflow and pressure drop to performance curves provided by blower manufacturers. Improper blower sizing results in an inability to deliver sufficient oxygen or a significantly shortened blower life. It is best to select the blower to allow operation near the middle of its performance range. A blower operating near its maximum pressure/vacuum is running inefficiently and under stressed conditions, thereby increasing operating costs and shortening its life. Selection of an oversized blower reduces operating efficiency and slightly increases capital costs, but is less detrimental than selection of an undersized blower.

Explosion-proof blowers are desirable for a bioventing system operating in the injection configuration and are required for blowers supplying vacuum to an extraction well. A blower supplying air to an injection well is not directly exposed to soil gases. However, explosive vapors may be present in the vicinity so an explosion-proof design should be used. Explosion-proof blowers must be used when the blower extracts soil gas that could contain flammable contaminants.

The airflow rate and pressure required for most bioventing projects can be provided by a blower in the capacity range of 2 to 10 hp. Blowers with intermediate-capacity range are available with 210-V or 240-V, single-phase or 480-V, three-phase motors. The 210-V or 240-V, single-phase versions are generally preferred for blowers in the 1.5- to 5-hp size range. The 480-V, three-phase version is preferred for blowers over 5 hp, due to its improved efficiency and lower current draw. However, the 240-V version can be used in situations where supplying 480-V service to the site would be difficult. The designer should determine the site's voltage supply capability before selecting the blower motor.

If the design airflow and system pressure drop indicate the need for a blower larger than 2 hp, the designer should consider dividing the system into separate groups of wells. Well groups would be designed to allow adequate air supply from a 1- or 2-hp blower.

Subdividing the system provides several advantages. Using several blowers increases reliability because failure of one blower does not shut down the entire bioventing system. Using several smaller units increases the ease and flexibility of installation. Lower power units can be supplied by low-voltage, low-current electrical service.

The blower should be protected from entry of foreign matter and water. For systems operating in the air injection configuration, an inlet air filter should be provided. For systems operating in the air extraction configuration, a moisture separation system such as a knockout drum or cyclone separator should be provided.

4.1.1.6 Design Vent Wells and Piping. Proper construction of vent wells and piping is essential for providing the required airflow to the soil. A typical bioventing well is shown in Figure 4. The [redacted]

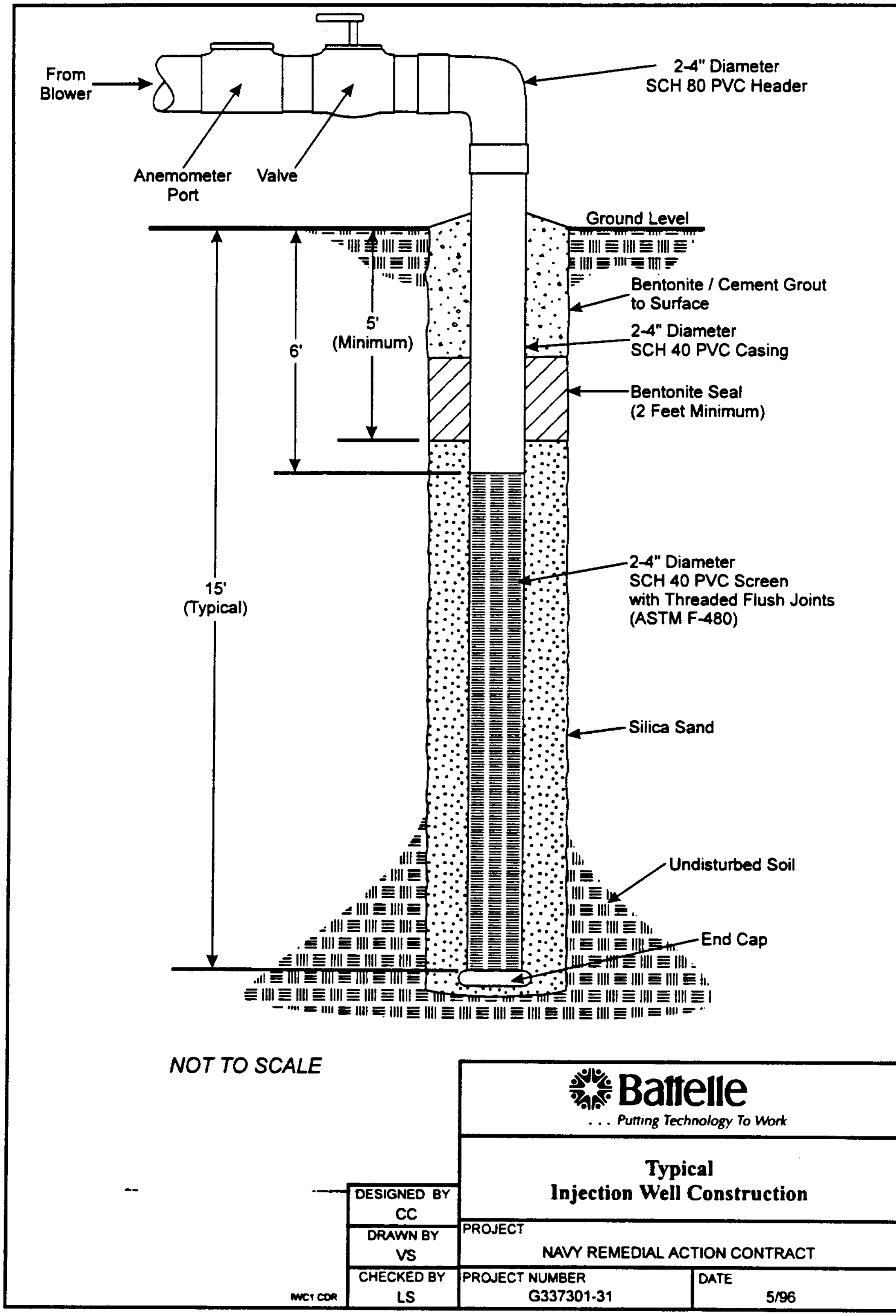


Figure 4. Illustration of a Typical Vent Well for Bioventing.

exceed the total grouted and sealed length. For example, in a well with 3 ft (0.91 m) of bentonite seal and 3 ft (0.91 m) of grout, the maximum allowed injection pressure is 72"H_2O (1.8×10^4 Pa).

Piping, valves, and instruments in the air supply piping should be designed to operate under the maximum design pressure plus a reasonable safety factor. Pressure- or vacuum-relief valves must be provided to ensure pressure conditions remain within the capabilities of the piping. Plastic piping made of PVC, chlorinated PVC (CPVC), polypropylene (PPE), or polyvinylidene fluoride (PVDF), is suitable for most installations. If high concentrations of solvent vapors are expected (air extraction configuration only), the piping system must be compatible with the vapors. Plastic piping that will be exposed to sunlight must be resistant to ultraviolet (UV) light or have a UV light protective coating applied.

Valves are needed to provide airflow control and shutoff capability. A bypass valve should be located at the blower outlet to allow discharge of excess blower airflow capacity. A flow control valve normally is provided for each vent well. Due to the infrequent adjustments needed, the cost to install automatically actuated valves rarely is warranted. Ball valves are reliable for shutoff service and provide adequate flow control precision for bioventing systems. Other types of valves, such as globe or needle valves, can be used but can increase cost with no improvement in performance. An access port for an anemometer should be located in the manifold piping to each vent well to provide the capability of measuring airflow into each well.

At a minimum, the following process control components must be included in the design for the bioventing system piping:

- capability to measure flowrate at each vent well
- blower motor thermal overload protection
- pressure/vacuum relief valve at the blower outlet
- sampling ports before and after air treatment equipment (extraction configuration only)
- level measurement in water knockout tank (extraction configuration only)
- pressure indicator at the blower outlet
- pressure indicator in the air distribution manifold
- pressure-relief valve or other overpressure protection at the blower outlet (purpose is to protect the blower motor from overheating, and protect the well seals)
- high-level switch and alarm for the condensate collection system (extraction configuration only)
- explosimeter [extraction configuration for site with recently measured vapor concentrations greater than 10% of the lower explosive limit (LEL)].

4.1.1.7 Determine Monitoring Point Locations and Design. Proper construction of monitoring points is essential for monitoring local pressure and soil gas composition in situ. Monitoring points typically are used to collect soil gas for carbon dioxide and oxygen analysis in the 0 to 25% range, and for hydrocarbons greater than 100 parts per million by volume (ppmv). The tubing material must have sufficient strength and be nonreactive. Appropriate materials include nylon and Tygon™. Sorption and gas interaction with the tubing materials have not been significant problems for this application. However, if a monitoring point will be used to monitor specific organics in the low-ppm or ppb range, Teflon™ or stainless steel may be necessary.

Monitoring point locations should be designed based on two general criteria:

- location of contamination
- soil parameters.

Whenever possible, monitoring points should be located in contaminated soils with greater than 1,000 mg/kg of total petroleum hydrocarbon (TPH). If monitoring points are not located in contaminated soil, meaningful in situ respiration data cannot be collected. The positions selected for monitoring points should consider soil gas permeability and R_I. Monitoring points should be located at varying radial distances from the vent well. The distances from the vent well will vary depending on soil type and vent well depth. An approximate guide for monitoring point spacing based on field experience is shown in Table 4. The actual placement of monitoring points will depend on contaminant location and other site-specific features. One monitoring point should be installed near the contaminated site in a location with similar geology but where there is no contamination.

Each monitoring point is usually a cluster of three gas sample collection tubes with each tube terminated with a screen. The screen allows soil gas to enter the sampling tube while holding the sand packing out. Each screen is positioned at a different depth with different colored tubes used to indicate the depth. Note that the interval to be sampled is backfilled with silica sand while the space between sample collection screens is filled with bentonite sealing material. For a few of the monitoring points, type J or K thermocouple wire should also be installed with the deep and shallow sampling tubes, with the temperature-reading bead located at the screen level. Figures 5 and 6 show the construction detail of a typical monitoring point installation.

The sample collection screens should be spaced to cover the vertical length of the monitoring point. Consideration should be given to potential seasonal water-table fluctuations and soil type before selecting the monitoring point depth. The deepest screen should be placed near the bottom of contamination, if the contamination ends above the water table. If contamination reaches to the water table, the deepest sample collection screen should be at least 2 to 3 ft (0.61 to 0.91 m) above the normal high-water-table level. In less-permeable soil, it must be screened further above the water table. The shallowest sample collection screen normally will be 3 to 5 ft (0.91 to 1.5 m) below land surface. The intermediate screen should be placed at a depth somewhere between the center and the upper one-fourth of the vent well screen. In some cases, it may be desirable to have more than three sampling tube depths to more fully monitor the contaminated interval, to monitor differing stratigraphic intervals, or to adequately monitor deeper sites with long vent well screens.

For sites with more than one well, it is not necessary to provide three monitoring points per vent well. A sufficient number of monitoring points should be installed to ensure representative sampling. The ratio of the number of monitoring points per number of vent wells can decrease as the number of vent wells increases, but a ratio of at least one monitoring point per vent well is recommended. The actual number installed is site-specific and is driven primarily by plume size and the cost of installing and monitoring additional monitoring points. If the air injection configuration is being used, several monitoring points must be located between injection wells and any structures that

Table 4. Recommended Spacing for Monitoring Points

Soil Type	Depth to Top of Vent Well Screen[a] (ft)	Radial Spacing of Monitoring Points Out from a Vent Well[b] (ft)
Coarse Sand	5	5-10-20
	10	10-30-50
	>15	20-30-70
Medium Sand	5	10-20-30
	10	15-25-45
	>15	20-40-70
Fine Sand	5	10-20-40
	10	15-30-50
	>15	20-40-60
Silts	5	10-20-40
	10	15-30-50
	>15	20-40-60
Clays	5	10-20-30
	10	10-20-40
	>15	10-25-50

(a) Monitoring point spacing assumes 10 ft of vent well screen. If more screen is used, the >15-ft spacing should be used.

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

may be within the radius of influence of the injection wells. Monitoring points must be available to ensure that the buildings are well beyond the radius of influence or that vapor-phase hydrocarbons are biodegraded before air reaches the structure.

4.1.2 Optional Design Features. This section describes the optional design elements of a full-scale bioventing system.

4.1.2.1 Extraction Versus Injection. Bioventing with air injection only is the most effective and lowest cost configuration for most sites. However, careful consideration must be given to the fate of the injected air. It may be necessary to extract air from some vent wells to prevent vapor movement into subsurface structures or to reduce air emissions from the surface. Air extraction wells may be required:

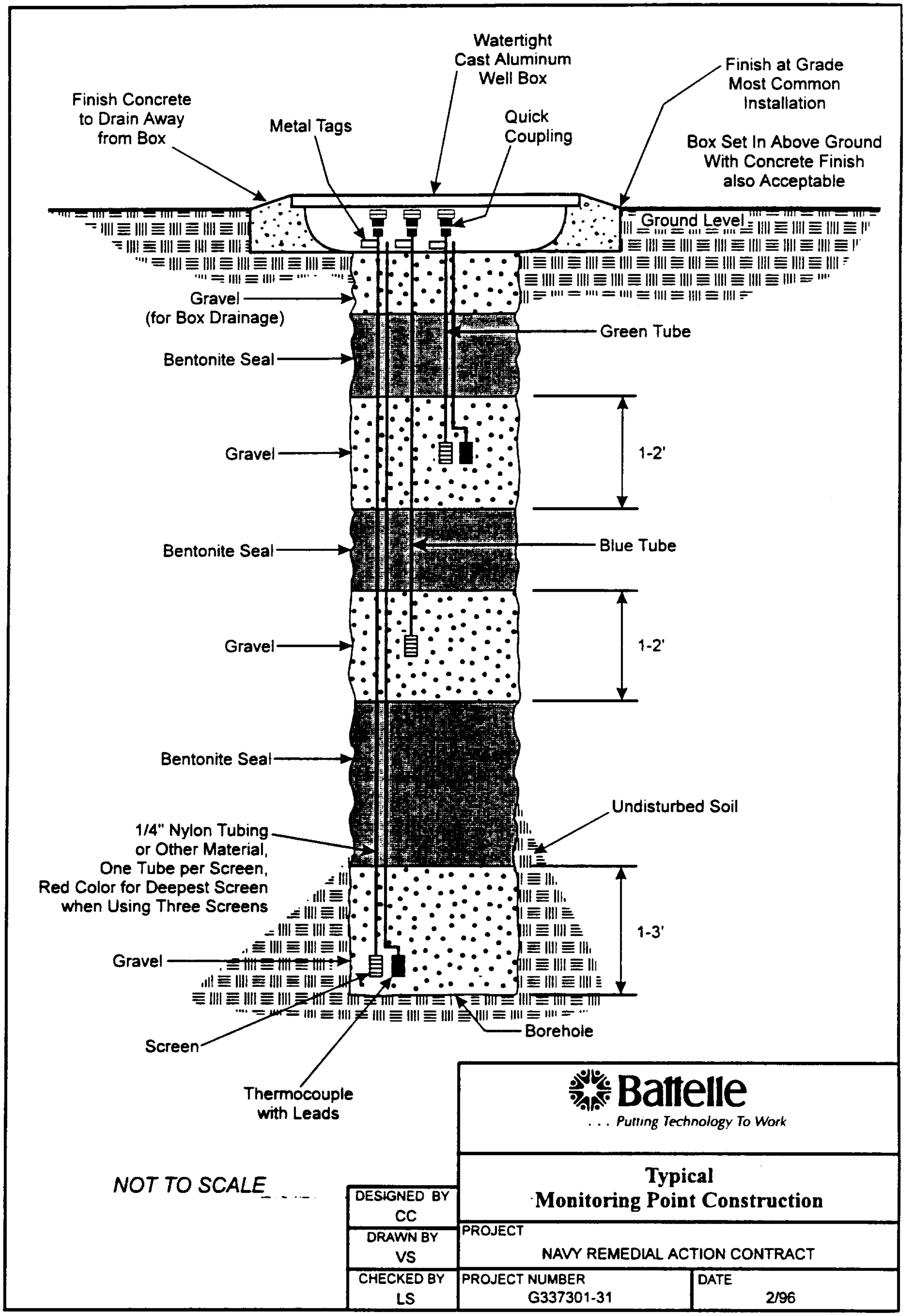
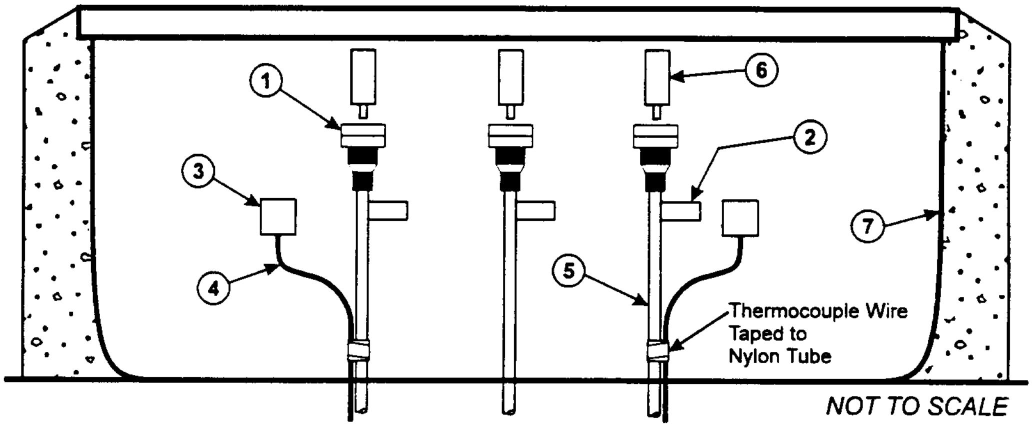


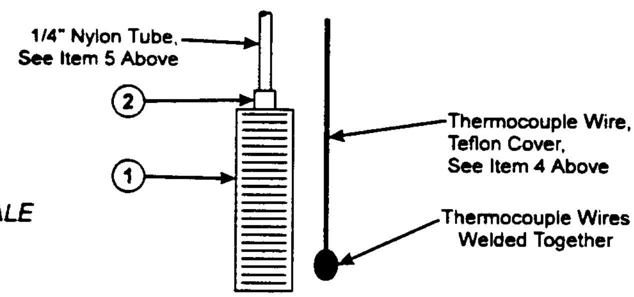
Figure 5. Illustration of a Typical Monitoring Point for Bioventing.



Item	Description
1	Quick Couplings, Parker 4Z-Q4CN-B or equivalent
2	Metal Tags, Seton Style SVT-15-Blank, 1.5" by 1.5" or equivalent
3	Thermocouple Plug, Cole Parmer 08509-62 or equivalent
4	Thermocouple Wire, L.H. Marshall K24-1-508 Teflon Cover, Type K or equivalent
5	Tubing, 1/4" O.D Nylon, New Age Flexible Grade, 0.070" I.D., various colors, or equivalent
6	Coupler Protector, Parker CP-Q4C-B or equivalent
7	Well Protector, Ace Manufacturing, Green Bay WI, or equivalent, cast aluminum, 9.7" O.D., 8.1" I.D.

(a) Details at Monitoring Point Well Box

NOT TO SCALE



Item	Description
1	Screen, Grainger 2P052 Suction Strainer or equivalent, with Connection Tapped 3/8-18 FPT; Screen Filled with Aquarium Gravel
2	Male Connector, Parker A4MC6

(b) Details at Screen

Battelle
. . . Putting Technology To Work

Construction Details at Well Box and Screen

DESIGNED BY CC			
DRAWN BY VS	PROJECT NAVY REMEDIAL ACTION CONTRACT		
CHECKED BY LS	PROJECT NUMBER G337301-31	DATE 3/96	

MPWELBOX.CDR

Figure 6. Construction Details at Well Box and Screen.

- if a building or other structure is located within the radius of influence of the injection wells to be installed at the site

- if the contamination is near a property boundary beyond which hydrocarbon vapors cannot be allowed.

Extraction wells usually supplement rather than totally replace injection wells because the extraction configuration has limitations.

Air extraction tends to decrease the proportion of contaminant biodegradation in comparison to volatilization. The optimal airflow rate for bioventing in either the injection or extraction configuration is the minimum required to satisfy the oxygen demand. Increasing air extraction rates will increase both volatilization and biodegradation rates until the site becomes aerated. Once the airflow rate is sufficient to fully aerate the soil, the biodegradation typically will be near its maximum so further increases in airflow do not increase biological destruction of contaminants. The rate of contaminant volatilization will continue to increase with increasing extraction rates until the contaminated soil system becomes diffusion-limited. Extraction systems result in some volatilization regardless of the extraction rate.

Air extraction can limit the ability to fully aerate the contaminated volume. Extraction wells create a partial vacuum in the soil causing the water table to rise. Because the bulk of contamination often lies several inches or feet above or below the water table (in the smear zone), the new higher water table can saturate much of the contaminated soil and reduce treatment efficiency. The upconing also will increase soil moisture in the capillary fringe and thus reduce soil gas permeability and the radius of influence in the capillary fringe.

Air extraction systems usually result in point source emissions that may require permitting and treatment. Air treatment will increase remediation costs significantly.

The decision to supplement injection wells with extraction wells usually is driven by safety considerations. Air injection alone should not be used unless a system can be designed that will not push hazardous vapors into structures or other unacceptable areas. Table 5 summarizes some of the considerations influencing the selection of bioventing system configuration with regard to injection and extraction. Note that the extracted air may be reinjected at a less sensitive area of the site (see Section 4.1.2.4).

Table 5. Considerations in Selecting Air Injection or Extraction Operating Configurations for Bioventing

Conditions Favoring Injection	Conditions Favoring Extraction
Low-vapor-pressure contaminants	High-vapor-pressure contaminants
Deep contamination	Surface emissions concern
Low-permeability soils	Structures/property boundaries within the R_I
Significant distance from structures/property boundaries	

4.1.2.2 Blower Options. The centrifugal regenerative blower is a reliable, low-cost method to provide the pressure rise needed to induce airflow in the bioventing system. However, rotary positive-displacement blowers may be selected at some sites. The ability of the positive-displacement machines to produce a high vacuum may be needed when soil is aerated in the extraction operating configuration. Twin lobe rotary blowers and water ring vacuum pumps are the two most common positive-displacement blower types selected, if a centrifugal blower is not used.

4.1.2.3 Passive or Solar-Powered Systems. Passive bioventing ~~or~~ solar-powered systems should be considered at remote locations or other sites where electrical power is unavailable and difficult to provide. Passive bioventing is implemented by placing a flapper valve in the vent well inlet. The flapper is arranged so that air flows freely into the vent well but cannot flow out. Daily barometric pressure changes provide the driving force. Solar-powered bioventing uses photovoltaic cells to generate direct current (DC) to power a DC motor that drives a blower. Because the motor operates only during daylight hours, the design airflow rate should be increased to account for the downtime.

4.1.2.4 Off-Gas Treatment Options. In keeping with the U.S. EPA's emphasis on pollution prevention, the bioventing system should be designed and operated to minimize off-gas release. The extraction configuration should be used only when needed (e.g., to prevent vapor buildup in a structure) and the extraction airflow should be kept as low as possible while still performing the required function. The options for treatment of vapor in extracted soil gas include:

- reinjection
- adsorption and media disposal
- adsorption and media regeneration
- thermal treatment in an internal combustion engine (ICE)
- thermal treatment in an incinerator
- thermal treatment in a catalytic oxidation unit
- biofiltration.

Off-gas treatment may be provided by reinjecting the extracted soil gas into a well located away from the area being protected by the extraction wells. Reinjecting the soil gas will enable the hydrocarbon vapors to biodegrade within the soil. Airflow into each reinjection well must be low enough that contaminants in the air are degraded by biological action in the soil. Use of reinjection may increase the need for surface emission monitoring due to regulatory concern about increased potential for contaminant migration.

A site may be unsuitable for reinjection due to either technical limitations such as low biodegradation rate or regulatory limitations. Where reinjection is not an acceptable option, conventional treatment methods are available. Release of vapors into ambient air is a long-standing problem in industry. A wide range of process options have evolved to remediate point source air releases (Mukhopadhyay and Moretti, 1993). The available options include adsorption and disposal, adsorption and regeneration, several implementations of thermal treatment, and biofiltration.

Adsorption using activated carbon without regeneration provides a simple and reliable method to treat off-gas. However, when the vapor concentration increases over about 1 ppmv, the cost becomes prohibitive (U.S. EPA, 1991, EPA/540/2-91/003).

Carbon regeneration allows economical operation with higher inlet vapor concentrations. Onsite carbon regeneration can be economical at a large chemical facility but is not practical for a typical bioventing site. Offsite regeneration services may be available in some areas.

Thermal treatment in an ICE, an incinerator, or a catalytic oxidation unit is more economical than adsorption when the vapor concentration is high. As the vapor concentration in the off-gas rises, the cost for adsorption increases due to disposal or regeneration costs but the cost for thermal treatment decreases due to lower fuel use. Thermal treatment in an ICE has achieved regulatory acceptance in some of the most stringent air quality districts in California and typically is competitive in cost with incineration or catalytic oxidation up to an off-gas flow of 500 standard cubic feet per minute (scfm). Treatment using an ICE is most cost effective when the inlet vapor concentration is over 25% of the LEL (about 4,000 ppmv).

Biofiltration has been used commercially for control of odor in off-gas. Application of biofiltration to treatment of hydrocarbon contaminants is a rapidly developing innovative off-gas treatment option that should be considered for low- to intermediate-concentration streams.

4.1.2.5 Modifications for Cold Weather Sites. The soil temperature significantly affects bioremediation. Microbial activity has been reported at temperatures varying from 10 to 212°F (−12 to 100°C) (Brock et al., 1984); however, the optimal range for biodegradation of most contaminants is generally much narrower. An individual microorganism may tolerate a temperature peak of up to approximately 104°F (40°C). However, a microorganism's optimal growth temperature will vary depending on climate. For example, microorganisms in a subarctic environment may exhibit optimal growth at 50°F (10°C), whereas microorganisms in a subtropical environment may exhibit optimal growth at 86°F (30°C). It has generally been observed that biodegradation rates double for every 18°FΔ (10°CΔ) temperature increase, up to some inhibitory temperature.

Heat addition may improve bioventing processes at cold weather sites. Options that have been tested or applied to provide supplemental heating for bioventing in cold climates include:

- solar warming
- warm water infiltration
- buried heat tape.

Supplemental heating has increased microbial activity and contaminant degradation rates while bioventing in arctic conditions (Leeson et al., 1995). Selection of the soil warming option depends on the added cost for heating compared to the savings gained by reduced remediation time. Characteristics of various soil warming methods are discussed by Smith and Hinchee (1992). Although use of warm water infiltration or heat tape can significantly increase biodegradation rates, the cost is significantly higher than simply using surface insulation or no heating. Warm water infiltration is effective but can be used only in permeable soils where the applied water will infiltrate rapidly before cooling. Soil heating to increase biodegradation rates may prove cost effective only in extremely cold regions, such as Alaska.

4.1.2.6 Modifications for Arid Sites. Soil moisture content influences the bioventing process by its effect on microorganisms and soil gas permeability. Microorganisms require moisture for metabolic processes and for solubilization of energy and nutrient supplies. Low soil moisture content can slow biodegradation but, conversely, a high soil moisture content reduces soil permeability resulting in poor distribution of oxygen in wet soils. The most common influence is excess moisture leading to significant reductions in soil gas permeability. In a few cases where bioventing has been implemented in dry desert environments, low soil moisture limits biodegradation rates.

At a desert site at the Marine Corps Air Ground Combat Center, Twentynine Palms, California, the low soil moisture content appeared to detrimentally affect microbial activity. Soil moisture ranged from 2% to 4% by weight and, although the site was contaminated with jet fuel, significant oxygen limitation was not observed. An irrigation system was installed at the site in an effort to enhance microbial activity. The site was irrigated for 1 week, then bioventing was initiated for 1 month before conducting an in situ respiration test. In situ respiration rates measured after irrigation were significantly higher than those measured prior to irrigation (U.S. Air Force and U.S. Environmental Protection Agency, 1995).

Implementing site irrigation requires careful monitoring of soil moisture to avoid excess moisture which reduces permeability and raises regulatory concerns about the potential for increased contaminant migration. As a minimum, gypsum blocks should be installed in monitoring points to allow measurement of soil moisture. Lysimeters, tubes to accept neutron moisture measurement probes, or both may be required in addition to the gypsum blocks.

4.1.2.7 Remote Monitoring. A computer-based data collection system with a modem communication link can be used to monitor and control bioventing system performance from a remote location. Relatively low-cost systems can be assembled using off-the-shelf personal computer components to monitor basic bioventing performance parameters. Use of remote monitoring can reduce the cost of system operation by reducing the number of required field inspections.

4.1.2.8 Groundwater Pumping for Water-Table Depression. Hydrocarbon contaminants may be smeared into soils below the normal water table due to seasonal fluctuations of the groundwater level. Bioventing cannot force air through the saturated zone. Contaminated soils below the water table can be remediated by bioventing by using groundwater pumping to depress the water table. Water-table depression can be achieved using standard groundwater pumping equipment. However, bringing groundwater to the surface can increase the cost and complexity of bioventing implementation due to the need to manage the water.

4.1.2.9 Free-Product Recovery. Bioventing will have limited success if a significant layer of floating free product is present. Free-product should be removed by pumping using conventional techniques or by vacuum-enhanced free-product recovery (bioslurping), which performs free-product removal and unsaturated zone aeration simultaneously.

4.2 Installation Requirements. This section describes techniques and precautions to apply during field installation of a full-scale bioventing system.

4.2.1 Minimum Required Installation Features. This section describes the requirements for installing a full-scale bioventing system.

4.2.1.1 Vent Well Installation. The methods available to install a vent well include:

- hollow-stem auger drilling
- solid-stem auger drilling

- hand auger drilling
- rotasonic drilling
- hydraulic pushing.

Selection of the method depends on many factors such as the depth to be reached, the soil type, and the number of wells to be installed. Hollow-stem augering is the most common drilling method for installing bioventing wells. A solid-stem auger is acceptable in more cohesive soils but using a solid-stem auger limits the ability to develop a meaningful as-built well log. A few shallow wells in sandy soils can be feasibly installed by hand-augering. Rotasonic drilling may be economical, if a large number of wells are required. Use of cone penetrometer (CPT)-pushed injection well points is being investigated for bioventing. Pushed points allow rapid, low-cost installation of venting points with minimal in situ disturbance.

Drilling methods that could smear the borehole wall or plug pores of unsaturated soil should not be used. For example, use of drilling mud should be prohibited and pushed points should not be used in soils with high clay content.

Sampling of the soils removed during drilling increases the understanding of the subsurface and enables better decisions to be made about final well installation details such as screen placement. A drilling log indicating the soil type encountered and as-built well diagrams should be prepared. Observations of features relevant to gas permeability such as shrinkage cracks, root holes, thin sand or clay layers, and moisture content are particularly important and should be recorded.

The annular space corresponding to the screened interval should be filled with silica sand or equivalent. The annular space above the screened interval should be sealed to prevent short-circuiting of air to or from the surface. The seal is formed by filling the annulus with bentonite chips, a bentonite grout slurry, or equivalent. The grout should be poured down a tremie pipe, if the placement is deeper than 15 ft (4.6 m).

Details of wellhead completion depend on other design features such as piping and instrumentation. Normally, each wellhead is fitted with a shutoff valve and an anemometer port. An appropriate pipe tee or elbow should be attached to the top of the well pipe riser to allow connection to the blower and installation of required valves and instruments. The well may be completed above or below grade. For wells that extend above grade, a small shelter or bollards may be needed to protect the wellhead. A vault with a cover is desirable to allow access to wells completed below grade.

The horizontal and vertical position of each well should be determined by survey. The required precision of the survey depends on project requirements, but a horizontal precision of 1.0 ft (0.33 m) and a vertical precision of 0.010 ft (3.3 mm) is acceptable in most applications.

4.2.1.2 Monitoring Point Installation. Monitoring point construction will vary depending on the drilling depth and technique. Although preparation of a borehole by augering is the most common method to install a monitoring point, direct-push methods can provide low-cost and effective monitoring points. Direct-push methods may be used where the soil type limits smearing of the opening wall (i.e. high sand content). As with the vent well installation, a borehole log should be prepared describing the soil type encountered during installation of the monitoring points.

Monitoring points installed in boreholes contain one or more sampling tubes. Such monitoring points consist of a cluster of small-diameter (¼-inch [6.4-mm]) tubes with each tube terminating at a specified depth with a screen approximately 6 inches (152 mm) long and 1 inch (25.4 mm) in diameter. Each tube should be identified with a metal tag and different color sampling tubes should be used to allow a consistent scheme of matching tube color to sample point depth. In shallow open-hole installations, schedule 80 ¼-inch (6.4-mm) PVC pipe terminating in the center of a gravel or sand pack may provide an adequate sampling point for collecting soil gas.

A permeable pack is provided to allow soil gas to flow to the sampling screen. The gravel or sand pack normally should extend for an interval of 1 to 2 ft (0.33 to 0.61 m), with the screen centered vertically and radially in the sand pack. In low-permeability soils, a larger particle size gravel pack may be desirable. In wet soils, a longer gravel pack with the screen near the top may be desirable.

A seal must be provided around sample collection levels. A seal at least 2 ft (0.61 m) thick normally is required above and below the permeable packing. The seal should be formed by pouring bentonite chips or granules into the borehole followed by addition of water to hydrate the bentonite.

For relatively shallow installations in more permeable soils, hand-driven sample points may be used. In such a system, a sacrificial drive point with Tygon™, Teflon™, or other appropriate tubing is driven to the desired depth. Then the steel outer tubing is retrieved, leaving the drive point and the inner flexible tubing in place. Hand-driven installation does not allow for sand pack or seal placement and should be used only in permeable soils where sample gas flow to the collection point is not limited or in soils that will "self heal" to prevent short-circuiting. Surface completion of the hand-driven points should be the same as for those installed in borings.

Temperature monitoring typically is conducted by attaching thermocouples to monitoring points. Type J or K thermocouples can be used and should be attached to the monitoring point screen at the depth of interest. In general, soil temperatures vary little across a site, but do vary with depth to the ground surface. Thermocouples are not required in every monitoring point for adequate soil temperature monitoring but thermocouples have a high failure frequency so redundant thermocouples should be installed at locations where temperatures are critical.

Gas sampling tubes should be terminated with quick disconnects to allow attachment of instruments or sample collection containers. Thermocouple wires should be terminated with connection plugs that are compatible with the thermocouple reader to be used on the project. The quick disconnects on the sampling tube ends and thermocouple terminals should be contained in a watertight cast aluminum well box, or equivalent, for protection.

Monitoring point locations should be determined using the methods and precision levels required for the vent wells.

4.2.2 Optional Installation Features. This section describes the options to consider when installing a full-scale bioventing system.

4.2.2.1 Buried Wellheads and Piping. In high-traffic or high-visibility areas, bioventing components can be installed in trenches that can then be backfilled. Locating the wellheads or piping (or both) below grade increases installation costs but may be advantageous. Bioventing often is selected because the remediation can proceed while normal work activities continue at the site. Buried wells and piping are simultaneously protected from and less likely to interfere with routine operations at the site.

4.2.2.2 Blower Shelter. The blower and associated mechanical and electrical components for the bioventing system should be placed in a secure and unobtrusive location. The components should be specified as weatherproof and should be able to operate continually while exposed to the weather. However, there are safety, performance, and appearance reasons for providing a shelter. The shelter can provide the following types of benefits

- preventing untrained personnel from accidently coming into contact with the equipment
- protecting components from the weather to increases reliability and longevity
- protecting components from unauthorized tampering
- reducing noise emissions from the blower.

The shelter should be painted to conform to nearby color schemes. The shelter may be a small shed or may be incorporated into portion of a operating trailer at the site. The enclosed space will seldom occupy a footprint greater than 3 ft × 4 ft (0.91 m × 1.22 m) and a height greater than 4 ft (1.22 m).

4.2.2.3 Use of Trenches or Horizontal Wells. Where the water table is near the surface, trenches or horizontal wells may be preferred. With a shallow water table, the contaminated area may be a thin band covering a wide area. Horizontal installation configurations allow greater areal coverage than do vertical wells. Horizontal configurations also minimize upwelling of the water table for systems using air extraction. Trenches or horizontal wells typically would be used only when the water table is located within about 10 ft (3.3 m) of the soil surface. A concern with the use of trenches for bioventing is the difficulty of sealing the back-filled soil sufficiently to prevent injected air from short circuiting to the surface.

Section 5: BIOVENTING OPERATION, MAINTENANCE, AND CLOSEOUT STRATEGY

Bioventing requires a period of operation and maintenance before cleanup goals can be reached. Bioventing typically will run for at least 1 year and may require several years at many sites. Well thought-out plans for operation, maintenance, and closeout are required to ensure high-quality, safe, and cost-effective operation. This section describes the features required for operation, maintenance, and closeout of a full-scale bioventing system and discusses optional features that may be required in special circumstances.

5.1 Operating Requirements. This section describes methods for operating a full-scale bioventing system.

5.1.1 Minimum Required Operating Features. This section describes the minimum activities required to start up and operate a full-scale bioventing system.

5.1.1.1 System Startup and Shakedown. The SOW should require performing and documenting the initial bioventing system startup and shakedown test shortly after installation is complete. A checklist for the initial inspection and shakedown of the bioventing system is provided in Table 6.

The startup test should be conducted to ensure all bioventing system components are installed and operating properly and to provide an initial setting for airflow balance. A visual inspection of the blower suction filter, the blower, the blower discharge piping and instrumentation, air injection wells, and monitoring points should be performed. It is particularly important to ensure that the inlet and discharge lines of the blower are not obstructed. Operation of the blower with low airflow due to starved suction or obstructed discharge will result in overheating and eventual damage to the blower. Field instrumentation should be visually examined, zero point checked and adjusted, and field calibrated. The initial pressures; temperatures; and soil gas concentrations of oxygen, carbon dioxide, and organic vapors should be measured at each level in each monitoring point.

The flow-control valve at each injection well should be fully opened and the bypass valve closed. Then the blower is switched on and the valve at each injection or extraction well is slowly adjusted to a partially closed position to provide approximately equal flow to each well, as determined using an anemometer in the anemometer port. The design flow for each well should be known and will be the target for adjustment. Of course, the total flow into all wells combined should be maintained at a rate within the design flow for the blower. Once balanced flow is achieved, the airflow rate at the inlet to each injection well and the airflow rate and pressure at the blower outlet should be recorded. If system airflow is too high, the bypass valve can be opened to discharge the excess.

Once the blower is running with balanced flow, the oxygen concentration in each monitoring point should be measured. The oxygen concentration in the soil gas in the monitoring points is the single most important control feature. Soil gas composition monitoring should be performed daily until the oxygen concentration in each monitoring point is stable. After constant oxygen concentration is reached in the monitoring points, the total airflow and position of the valves controlling the flow to each air injection or extraction well should be adjusted to give a minimum 10% oxygen in soil gas sampled from each monitoring point. Airflow rates should not be readjusted until the soil gas oxygen concentration stabilizes so that the in situ soil system equilibrates before the next adjustment.

Table 6. Example Bioventing System Startup Checklist

Bioventing System Startup Checklist

Site: ____________________________

Date: ____________________________ Operator's Initials: __________

Activity	Check when done	Data/Comments
Ensure that the blower inlet filter is installed and clear		
Inspect blower		
Inspect blower discharge piping		
Ensure grounding connections are properly installed and functional		
Inspect and manually cycle valves		
Inspect instruments at each injection well		
Ensure that the injection wells were installed per specification		
Ensure that wells were purged and cleaned		
Inspect condition of monitoring points		
Ensure that off-gas treatment system (if required) is installed and operational		
Ensure that off-gas treatment system fuel supply (if required) is available		
Check and field-calibrate instruments: GasTech™ O_2/CO_2 analyzer TraceTector™ hydrocarbon analyzer Fluke™ thermocouple reader		
Measure pressure and soil gas composition in monitoring points		Attach data sheets
Ensure all airflow balancing valves are open		
Start blower		
Adjust equal airflow to each well		
Measure airflow at inlet of each injection well		Attach data sheets
Measure airflow and pressure at outlet of blower		Attach data sheets
Measure pressure and soil gas composition in monitoring points		Attach data sheets
Repeat monitoring point measurements until oxygen concentrations stabilize		Attach data sheets
Stop blower and perform shutdown in situ respiration test[(a)]		Attach data sheets
Restart blower[(a)]		
Readjust airflow balance based on oxygen (and in situ respiration[(a)]) measurements		
Remeasure airflow at inlet of each injection well		Attach data sheets
Remeasure airflow and pressure at outlet of blower		Attach data sheets
Perform surface emission test[(a)]		Attach data sheets

(a) Optional startup testing activities.

5.1.1.2 Routine Operations. Once installed, the bioventing system should be operated in a flexible manner to optimize biological destruction of contaminants while limiting the quantity of contaminants removed by vapor transport. Periodic monitoring is required to measure system performance, and system adjustments may be needed to adapt to declining contaminant concentrations or other changing conditions at the site.

Once the preliminary airflow balancing is completed, a routine schedule of operating checks should be established and documented. A walkby check to confirm normal operation of the system should be performed weekly. The walkby should include visual inspection of the blower and wellheads. The weekly check should be supplemented monthly by a more complete set of checks and measurements. Monthly checks and measurements include:

- date and time of measurements
- ambient air temperature, barometric pressure, and cumulative precipitation
- depth to groundwater
- a visual inspection of the components as described in the shakedown test
- measurement of soil gas concentrations of oxygen, carbon dioxide, and organic vapors; pressures; and temperatures in each monitoring point
- the airflow rate, pressure, and temperature at the inlet to each injection.

If the monthly measurements indicate that the oxygen concentration in soil gas near a well is below 5% to 8%, the airflow to the well should be increased. Similarly, if the oxygen concentration in soil gas near a well approaches 20%, the airflow to the well should be decreased.

The frequency of measurement of pressures; temperatures; and soil gas concentration of oxygen, carbon dioxide, and organic vapors; can be reduced once the values stabilize. Stabilization will occur at most sites within 3 months. After conditions stabilize, measurements should be taken once during the winter and once during the summer and annually thereafter.

In situ respiration testing should be performed in each of the monitoring points twice in the first year and annually thereafter. The two initial in situ respiration tests should span typical temperature conditions at the site (i.e. one test during cool to cold weather and the other during moderate to hot weather).

A checklist for the periodic inspection of the bioventing system is provided in Table 7.

5.1.1.3 Maximum Allowed Operating Pressure. To maintain the integrity of the vent well seal, do not allow injection pressures measured in water head to exceed the total grouted and sealed length. For example, in a well with 3 ft (0.91 m) of bentonite seal and 3 ft (0.91 m) of grout, the maximum allowed injection pressure is 72"H_2O (1.8×10^4 Pa).

5.1.2 Optional Operating Features. This section describes the activities that may be used during startup and operation of a full-scale bioventing system under special conditions.

Table 7. **Example Bioventing System Periodic Inspection Checklist**

Bioventing System Periodic Inspection Checklist

Site: ______________________

Date: ______________________ Operator's Initials: __________

Activity	Check when done	Data/Comments
Record ambient air temperature (monthly)		
Record barometric pressure (monthly)		
Record cumulative precipitation (monthly)		Note starting date for precipitation data
Measure depth to groundwater (monthly)		
Ensure that blower inlet filter is installed and clear (weekly)		
Inspect blower (weekly)		
Inspect blower discharge piping (weekly)		
Inspect instruments at each injection well (weekly)		
Inspect injection wells (monthly)		
Inspect condition of monitoring points (monthly)		
Check and field-calibrate instruments (monthly) GasTech™ O_2/CO_2 analyzer TraceTector™ hydrocarbon analyzer Fluke™ thermocouple reader		
Measure pressure and soil gas composition in monitoring points (monthly)		Attach data sheets
Measure airflow at inlet of each injection well (monthly)		Attach data sheets
Measure airflow and pressure at outlet of blower (monthly)		Attach data sheets
Perform in situ respiration test[a]		Attach data sheets
Perform surface emission test[b]		Attach data sheets

(a) Perform in situ respiration tests twice in the first year and annually thereafter.
(b) Perform after significant changes in airflow balance or in situ pressures, if required.

5.1.2.1 Detailed System Flow Balancing. Detailed flow balancing may be required to optimize air supply to the soil, particularly at a site with complex in situ geology. The blower is started and adjusted as described in the "System Startup and Shakedown" section above.

Once the blower is running with balanced flow, the oxygen and carbon dioxide concentration in each monitoring point should be measured. Soil gas composition monitoring should be performed daily until the soil gas composition in each monitoring point is stable. After constant soil gas composition is reached in the monitoring points, the blower should be shut off. In situ respiration rates should be determined at each monitoring point by measuring the oxygen and carbon dioxide concentration changes with time after the blower is shut off.

Data showing the highest oxygen concentration achieved during air injection and the in situ respiration rates in monitoring points around each well are then used to assist in a preliminary optimization of flow rates into each injection well. Wells where the highest oxygen concentration achieved in the balanced flow case is less than 5% to 8% or where the shutdown in situ respiration test measured high degradation rates should receive a larger share of the flow. Conversely, wells where the oxygen concentration approaches 20% or where the contaminant degradation rates were low should receive reduced airflow. The blower should be restarted and the airflow into each well rebalanced based on the measured data.

5.1.2.2 Surface Emission Testing. A surface emission test may be required for bioventing systems operated in the injection configuration. Surface emission testing typically is not done but may be required to satisfy local regulations. Emission testing frequency must be specified to meet regulatory requirements. Surface emission testing methods are described in (U.S. Air Force and U.S. Environmental Protection Agency, 1995).

5.1.2.3 Off-Gas Treatment System Operation. Use of an off-gas treatment, due to operation in the extraction configuration, will significantly increase the operating complexity. The operating requirements are specific to the type of system selected. Requirements should be set consistent with the manufacturer's direction and regulatory requirements.

5.1.2.4 Carbon Isotope Ratio Monitoring. Measurement of stable carbon isotope ratios may help verify that hydrocarbon biodegradation is taking place (Aggarwal and Hinchee, 1991). The isotopic composition of carbon is expressed as $\delta^{13}C$, which is the ratio of ^{13}C to ^{12}C measured in parts per thousand, expressed relative to a standard. A commonly used standard is fossil shell deposits with a $^{13}C/^{12}C = 0.01124$. The $\delta^{13}C$ value is given as

$$\delta^{13}C = \frac{(^{13}C/^{12}C)_{sample} - (^{13}C/^{12}C)_{standard}}{(^{13}C/^{12}C)_{standard}} * 1000 \qquad (3)$$

Carbon dioxide produced by hydrocarbon degradation may be distinguished from that produced by other processes based on the carbon isotopic compositions characteristic of the source material or the fractionation accompanying microbial metabolism. Carbon dioxide generated from natural organic material has a $\delta^{13}C$ of approximately -10 to -15, whereas carbon dioxide generated from petroleum hydrocarbons has a $\delta^{13}C$ of approximately -20 to -30. This measurement is not required to validate biodegradation, because the in situ respiration test is used for this purpose; therefore, it should be conducted only if dictated by regulatory concerns.

5.2 Maintenance Requirements. Bioventing systems are not immune to wear and breakage, but a number of factors work to minimize the maintenance required for routine operation of a bioventing system. Bioventing systems operate at steady state for long periods, so complex control equipment and remotely actuated valves are not needed. Use of high-wear items such as electrical contacts and rotating or sliding seals is minimized, and where they are used, cycling occurs infrequently. Also, the types of equipment used have been through several generations of refinement in industrial service and have reached an advanced state of development for reliable operation. Nevertheless, routine maintenance must be performed to ensure continued reliable operations.

5.2.1 Minimum Required Maintenance Features. This section describes the minimum activities required to maintain a full-scale bioventing system.

5.2.1.1 Vent Well Maintenance. Increased airflow into a well, reduced pressure at the well inlet, and reduced radius of influence around the well are various indications of leakage from the well seal. If well conditions indicate a leaking seal, the seal condition should be checked. Either of two methods may be used to diagnose well seal integrity. In the first method, a soap solution is coated onto the surface of the seal while the well is pressurized. Bubbling indicates a seal leak. In the second method about 1 gal (3.8 L) of water is poured onto the grout around the well. The water will soak into a severely damaged seal in minutes. A sound seal will hold the water out for more than an hour (USACE, 1995).

A leaking seal must be repaired. Small leaks can be repaired by removing the well from service and adding a new layer of grout. Well seals that are visibly cracked must be removed and replaced.

5.2.1.2 Blower Maintenance. The visual observation of plugging or decreased outlet pressure indicates plugging of the blower inlet air filter. The plugged filter should be replaced immediately.

The blower should be lubricated and maintained in accordance with the manufacturer's directions. The requirements will vary depending on the type of blower used. Centrifugal regenerative blowers typically are supplied with long-running, self-lubricating seals and require minor routine maintenance. Rotary lobe blowers may require periodic lubrication. Water ring vacuum pumps may require inspection and adjustment of the water level in the seal level maintenance tank.

5.2.2 Optional Maintenance Features. This section describes the activities required to maintain a full-scale bioventing system under special conditions.

5.2.2.1 Off-Gas Treatment System Maintenance. Use of an off-gas treatment, due to operation in the extraction configuration, will significantly increase the maintenance complexity. The maintenance requirements are specific to the type of system selected. Requirements should be set consistent with the manufacturer's direction and regulatory requirements.

5.3 Project Closeout Requirements. Completion of a site remediation with bioventing requires establishing and documenting statistical evidence that the cleanup goals have been reached.

5.3.1 Minimum Required Project Closeout Features. This section describes the minimum activities required to close out a full-scale bioventing system.

5.3.1.1 Soil Gas Sampling. In situ respiration testing should be used as the primary indicator for starting site closure procedures. The number of samples required to demonstrate a statistically valid conclusion renders the cost of soil analysis prohibitive until contamination levels approach 90 to 99% of the cleanup goal. The cost of sampling and analysis is a significant portion of the overall cost of a bioventing project. Minimizing soil sampling will make a remediation effort much more cost effective.

With bioventing systems, in situ respiration testing can indicate when the site is clean and therefore when to collect final soil samples. As site remediation progresses and contaminants are degraded, the measured in situ respiration rates will approach background respiration rates. When the in situ respiration rate in the contaminated area approaches that in the uncontaminated area, this is a good indication that the site is remediated and final soil sampling can be conducted. The oxygen concentration should be measured in soil gas taken from a nearby uncontaminated location with a geology similar to that of the contaminated area. If the oxygen content in soil gas is greater than 15% in the uncontaminated location, the background respiration rate is low and no further measurements are needed. If the oxygen content in soil gas is less than 15%, the background in situ respiration rate should be measured in the uncontaminated area.

5.3.1.2 **Soil Analysis.** For nearly all sites, soil cleanup goals are stated in terms of contaminant concentrations in soil. A variety of approaches are conceptually possible for defining the required cleanup goals for a bioventing site, but in practice soil sampling is the most common method used to demonstrate compliance. However, due to the high cost and potential disruption to site operations, soil sampling should not be used for routine process monitoring.

The number of final soil samples collected usually is driven by a regulatory requirement to demonstrate a high confidence that the required cleanup goals have been achieved. The plan for collecting soil samples should be designed on a sound statistical basis as described in ASTM D 4687, "Standard Guide for General Planning of Waste Sampling." Sample locations should be selected using a simple random or systematic random probability method so that analytical results can be evaluated using statistical theories.

Different cleanup goals will be specified if different contaminants are present. Petroleum hydrocarbons are the most common contaminant treated by bioventing, so the most common cleanup goal specification is based on TPH. Benzene, toluene, ethylbenzene, and xylenes (BTEX) frequently are components of petroleum hydrocarbon materials. The BTEX compounds are more mobile and toxic than TPH compounds. When BTEX compounds are present, the cleanup goals required for these compounds will be lower than for TPH.

Laboratory determination of concentrations of organic compounds in soils typically is performed in two steps:

- collection of the compounds from the soil
- detection of the collected compounds.

Collection may be accomplished either by a purge-and-trap method or by an extraction method. Purge-and-trap methods (e.g., EPA SW-846 Method 5030) are most appropriate for volatile organic compounds (VOCs) such as gasoline or BTEX. Extraction methods (e.g. EPA SW-846 Method 3510) are more appropriate for semivolatile organic compounds (SVOCs) such as the main TPH components of diesel fuel or heavy oil.

Detection can be accomplished by gas chromatography combined with photoionization detector (GC/PID), gas chromatography combined with a flame ionization detector (GC/FID), or gas chromatography combined with a mass spectrometer (GC/MS). EPA SW-846 Method 8015 describes both GC/PID and GC/FID detection approaches. The FID detects flammable compounds giving nearly universal response to hydrocarbons, whereas the PID tends to have higher sensitivity for aromatics in comparison to aliphatics. Based on its sensitivity characteristics, the FID is used for detection of nonspecific hydrocarbons and the PID is favored for BTEX analysis.

An example of the GC/MS detection approach is described in EPA SW-846 Method 8240. The GC/MS method costs more per sample but can quantify both BTEX and TPH compounds. When both BTEX and TPH results are needed, a GC/MS approach may be more cost effective than separate analyses for BTEX and TPH.

The measured concentration of hydrocarbons in soils typically shows wide variability due to the heterogeneous distribution of contaminants in the soil. Statistical analysis is needed to allow a meaningful comparison of the results with the action limit. Typically the upper confidence limit (UCL) of the mean of the distribution of contaminant concentrations is compared to the action limit. The UCL must be determined by applying the statistical analysis for the appropriate distribution type. The analytical results should be checked to determine how they are distributed (Gilbert, 1987). The population may be distributed in one of the following ways:

- normally
- log-normally
- nonparametrically.

Although many populations of environmental contaminant concentrations are log-normally distributed, a log-normal distribution should not be assumed without justification (U.S. EPA, 1989, EPA/530-SW-89-026).

A confidence level of 100% would be desirable but would require taking an infinite number of samples so the acceptance of cleanup is usually based on the 95% UCL. If the calculated 95% UCL is below the cleanup goal, the site cleanup is complete. If the 95% UCL is slightly above the cleanup goal, additional sampling may result in lowering the UCL, particularly when the standard deviation of the distribution is large. The decision of taking additional samples or continuing the remediation includes consideration of:

- the cost of sampling versus the cost of continued remediation
- the current in situ respiration rate
- consideration of regulatory acceptance.

5.3.1.3 Well Abandonment. Well abandonment and plugging procedures should ensure that (1) the well does not become a source or channel for groundwater contamination and (2) the well does not allow a pathway for pressure loss from a confined aquifer. Abandonment and plugging typically require that the well be filled with cement, bentonite slurry, or crushed bentonite and then capped with a cement plug. Many states and localities have regulations providing specific technical and documentation requirements for well abandonment. In all cases, the local regulations should be considered as the minimum requirement.

5.3.1.4 Documentation. Attainment of cleanup goals and completion of bioventing project closeout activities should be documented in a site closure certification report. Before preparing the closure report, the contractor should determine the format and content required by the lead regulatory agency. A typical closure certification report will cover the following topics areas:

- site history, contaminants, cleanup goal, and remedial actions
- the results of sampling and analysis to ensure attainment of cleanup goals
- a description of well abandonment activities
- any measures required for permanent site maintenance [the Operations and Maintenance (O&M) Plan]
- any required deed restrictions.

5.3.2 Optional Project Closeout Features. This section describes an activity that may be required to closeout a full-scale bioventing system under special conditions.

5.3.2.1 Deed Restrictions. If cleanup goals are developed from a risk assessment that assumes the site will continue in a similar industrial use, a deed restriction may be required. The deed restriction notifies potential future buyers of limitations on the use of the property. The deed restriction should be prepared by an attorney licensed to practice in the state where the site is located and should be filed with the appropriate local real property deed recording agency. For bases not scheduled for closure, recognition of the contaminated site locations in the facilities land use plans may be sufficient to satisfy regulatory concerns that projected future uses of the site not change without evaluation.

Section 6: QUALITY ASSURANCE

The project must include construction quality management (CQM) procedures to ensure that the methods and materials used in design, construction, operation, maintenance, and closeout meet the project specifications and requirements. These requirements are derived methods, standards, and specifications from sources such as:

- U.S. Department of Defense
- American Society for Testing and Materials
- American National Standards Institute
- American Petroleum Institute
- American Water Works Association
- Institute of Electrical and Electronics Engineers
- National Fire Protection Association
- Underwriters Laboratory

or from regulatory requirements stated in

- permit modifications
- orders
- records of decision.

Construction quality management is defined as the proactive planning, development, and implementation of both construction quality control (CQC) and construction quality assurance (CQA) throughout the project. Construction quality control (CQC) is an ongoing process of measuring and controlling the characteristics of work elements so that the elements meet the manufacturer's or project specifications. Construction quality assurance (CQA) is a planned series of observations and tests performed to measure the final quality and document that the bioventing system meets project specifications. To ensure that a functional and safe bioventing system is implemented, all parties involved in the project must take responsibility for implementing CQM. CQM must be incorporated into all phases of the project, including:

- preconstruction
  - conceptual design
  - design
  - specification preparation
  - CQA/CQC document preparation

- construction
  - material property testing
  - installation testing
  - installation inspection

- postconstruction
  - care of installation prior to startup
  - inspection and maintenance of the installation
  - operation
  - closeout.

To achieve CQM objectives, bioventing work elements are separated into definable features of work (DFW) according to similarity in their implementation and testing requirements. A DFW may be an activity, task, or set of tasks which use similar material, handling, or inspection methods and that are controlled by the requirements of the same specifications. Typical DFW for a bioventing project are:

- preconstruction submittals
- well drilling and installation
- chemical and geochemical analysis
- site preparation
- support pad installation
- blowers, piping, and mechanical equipment
- electrical equipment
- instrumentation
- finishes
- bioventing system startup, operation, and maintenance
- postconstruction submittals.

Section 7: HEALTH AND SAFETY

The bioventing system must be designed and implemented to maximize protection of health and safety for workers and the public. System designs must incorporate features to avoid unsafe conditions and activities. Site activities must be controlled by a site-specific health and safety plan (HASP). The HASP must assign roles and responsibilities, establish standard operating procedures, and provide for safety contingencies. Field activities must comply with the provisions of 29 CFR 1910.120, "Hazardous Waste Operations and Emergency Response" and other Occupational Safety and Health Administration (OSHA) requirements. All laboratory activities must comply with the OSHA chemical hygiene standards defined in 29 CFR 1910.1450. Safety and Health Standards generally applicable to protection of workers at bioventing sites are summarized in Table 8.

Appropriate safety and health plans and procedures must be developed and followed for all aspects of bioventing system installation and operation. The plans and procedures must include methods to mitigate hazards specific to bioventing implementation. Some of the hazards specific to

Table 8. Applicable Health and Safety Regulations

Topic	Reference
General Industry Standards	29 CFR Part 1910
Walking and working surfaces	Subpart D 1910.21-.32
Occupational noise exposure	Subpart G 1910.95
Hazardous Waste Operations and Emergency Response	Subpart H 1910.120
Personal protective equipment	Subpart I 1910.132-.140
Sanitation	Subpart J 1910.141
Medical and first aid	Subpart K 1910.151-.153
Toxic and hazardous substances	Subpart Z 1910.1000-.1500
Construction Industry Standards	29 CFR Part 1926
Occupational health and environmental controls	Subpart D 1926.50-.57
Personal protective and life-saving equipment	Subpart E 1926.100-.107
Fire protection	Subpart F 1926.150-.155
Signs and signals	Subpart G 1926.200-.203
Motor vehicles and mechanical equipment	Subpart O 1926.600-.604
Excavations, trenching, and shoring	Subpart P 1926.650-.652
Power transmission and distribution	Subpart V 1926.950-.957

bioventing system installation and operation are summarized in Table 9. Table 9 also indicates the typical source of the hazard and some possible mitigation methods.

Table 9. Hazard Sources and Mitigation in Bioventing Implementation

Hazard	Typical Hazard Sources	Possible Mitigation Methods
Flying particulates	Rotating equipment such as drilling rigs or blowers	Safety glasses
Binding in equipment	Rotating equipment such as drilling rigs or blowers	Shields to prevent contact with rotating equipment
Objects striking head	Overhead operations such as drilling rigs	Proper rigging practices Hard hats
Objects striking foot	Overhead operations such as drilling rigs	Proper rigging practices Steel-toed shoes
Slips, trips, and falls	General site hazards	Good housekeeping Limit access to site with fencing
Exposure to organic contaminants in soil or organic liquids	Organic contaminants	Monitoring Good housekeeping Gloves, coveralls, boot covers
Exposure to organic vapors	Organic contaminants	Monitoring Respirators
Severing a utility line	Drilling or trenching	Obtain clearance before drilling or digging Mark location of known utilities
Electric shock	Power supply to mechanical equipment and instruments	Follow local utility codes Do not use temporary wiring Disconnect, tag, and lock out power supply before doing maintenance (see OSHA 29 CFR 1910.147)

Table 9. Hazard Sources and Mitigation in Bioventing Implementation (continued)

Hazard	Typical Hazard Sources	Possible Mitigation Methods
Contacting overhead wires	Drilling rig	Do not move drilling rig with tower deployed Do not deploy drilling tower near overhead wires
Fire and explosion	Organic vapors	Use explosion-proof equipment Monitor Provide ventilation for enclosures (e.g. blower shelter)
Fire and explosion	Off-gas incinerator or catalytic oxidation unit (if used)	Comply with National Fire Protection Association requirements Never allow concentration of vapor in the inlet to exceed 25% of LEL
Contact with high-temperature surfaces	Thermal off-gas treatment equipment (if used)	Insulation or expanded metal shields to prevent access
Noise	Drills, pumps, blowers Nearby aircraft or vehicles	Monitor Hearing protection equipment (see OSHA 29 CFR 1910.95)
Vehicle hazards	Site vehicle operations (e.g., drilling rig, front-end loader, or forklift)	Train and license personnel for operation of site equipment
Traffic	Vehicle operations near the site	Distinctive marking, lights, and barricades Limit access to site with fencing

Section 8: REFERENCES

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APPENDIX A

EXAMPLE CONTENT FOR A SCOPE OF WORK FOR CORRECTIVE MEASURE IMPLEMENTATION

(Adapted from U.S. Environmental Protection Agency. 1986b. OSWER Directive 9902.3, *Interim Final Corrective Action Plan*. Office of Emergency and Remedial Response, Washington, DC. November.)

SCOPE OF WORK FOR THE CORRECTIVE MEASURE IMPLEMENTATION AT [SPECIFY FACILITY NAME]

PURPOSE

The purpose of this Corrective Measure Implementation (CMI) program is to design, construct, operate, maintain, and monitor the performance of the corrective measure or measures selected to protect human health and the environment. The Respondent will furnish all personnel, materials, and services necessary to implement the corrective measure or measures.

[Note: This example scope of work is intended to foster timely development of concise SOWs. To achieve this goal, facility-specific conditions should be considered when using the model scope of work. This scope should be modified as necessary to require only information necessary to complete the CMI.]

SCOPE

This program consists of four tasks;

Task I: Corrective Measure Implementation Program Plan
- A. Program Management Plan
- B. Community Relations Plan

Task II: Corrective Measure Design
- A. Design Plans and Specifications
- B. Operation and Maintenance Plan
- C. Cost Estimate
- D. Project Schedule
- E. Construction Quality Assurance Objectives
- F. Health and Safety Plan
- G. Design Phases

Task III: Corrective Measure Construction
- A. Responsibility and Authority
- B. Construction Quality Assurance Personnel Qualifications
- C. Inspection Activities
- D. Sampling Requirements
- E. Documentation

Task IV: Reports
- A. Progress
- B. Draft
- C. Final.

TASK I: CORRECTIVE MEASURE IMPLEMENTATION PROGRAM PLAN

First, the Respondent shall prepare a CMI Program Plan. Program planning will include the development and implementation of several plans, which are prepared at the same time. It may be necessary to revise plans as the work is performed to focus efforts on a particular problem. The Program Plan includes the following:

A. Program Management Plan

The Respondent shall prepare a Program Management Plan to document the overall management strategy for performing the design, construction, operation, maintenance, and monitoring of corrective measure(s). The plan shall document the responsibility and authority of all organizations and key personnel involved with implementation. The Program Management Plan also shall include a description of qualifications of key personnel directing the CMI Program, including contractor personnel.

B. Community Relations Plan

The Respondent shall revise the Community Relations Plan to include any changes in the level of concern of information needs to the community during design and construction activities.

1. Specific activities which must be conducted during the design stage are the following:

    a. Revise the facility Community Relations Plan to reflect knowledge of citizen concerns and involvement at this stage of the process; and

    b. Prepare and distribute a public notice and an updated fact sheet at the completion of engineering design.

2. Specific activities to be conducted during the construction stage could be the following: Depending on citizen interest at a facility at this point in the corrective action process, community relations activities could range from planning group meetings to distributing fact sheets on the technical status.

TASK II: CORRECTIVE MEASURE DESIGN

The Respondent shall prepare final construction plans and specifications to implement the corrective measure(s) at the facility as defined in the Corrective Measure Study.

A. Design Plans and Specifications

1. Discuss the design strategy and the design basis, to:

    a. Ensure compliance with all applicable or relevant environmental and public health standards; and

    b. Minimize environmental and public impacts.

2. Discuss the technical factors of importance including:

    a. Use of currently accepted environmental control measures and technology;

    b. The constructability of the design; and

    c. Use of currently acceptable construction practices and techniques.

3. Describe assumptions made and provide a detailed justification of these assumptions;

4. Discuss the possible sources of error and references to possible operation and maintenance problems;

5. Provide detailed drawings of the proposed design, including:

    a. Qualitative piping and instrument; and

    b. Quantitative mass and energy balance diagrams.

6. Provide tables listing equipment and specifications;

7. Provide tables giving material and energy balances;

8. Include these appendices:

    a. Sample calculations (present one example and clearly explain significant or unique design calculations);

    b. Derivation of equations essential to understanding the report; and

    c. Results of laboratory or field tests.

B. Operation and Maintenance Plan

The Respondent shall prepare an Operation and Maintenance Plan to cover implementation and long-term maintenance of the corrective measure. The plan shall be composed of the following elements:

1. Description of normal operations and maintenance (O&M):

    a. Describe tasks for operation;

    b. Describe tasks for maintenance;

    c. Describe prescribed treatment or operation conditions; and

    d. Provide schedule showing frequency of each O&M task.

2. Description of potential operating problems:

    a. Describe and analyze potential operating problems;

    b. Provide sources of information regarding problems; and

    c. List common and/or anticipated remedies.

3. Description of routine monitoring and laboratory testing:

    a. Describe monitoring tasks;

    b. Describe required laboratory tests and their interpretation;

    c. State QA/QC requirements; and

    d. Provide schedule of monitoring frequency and date, if appropriate, when monitoring may cease.

4. Description of alternative O&M:

    a. Provide alternative procedures to prevent undue hazard should systems fail; and

    b. Provide analysis of vulnerability and additional resource requirements should a failure occur.

5. Safety plan:

    a. Describe precautions, necessary equipment, etc., for site personnel; and

    b. List safety tasks required in event of systems failure.

6. Description of equipment:

   a. Identify equipment;

   b. Give instructions for installing monitoring components;

   c. Give instructions for maintenance for site equipment; and

   d. Provide replacement schedule for equipment and installed components.

7. Records and reporting mechanisms required:

   a. Daily operating logs;

   b. Laboratory records;

   c. Records for operating costs;

   d. Mechanism for reporting emergencies;

   e. Personnel and maintenance records; and

   f. Monthly/annual reports to state agencies.

   An initial Draft Operation and Maintenance Plan shall be submitted simultaneously with the Prefinal Design Document submission, and the Final Operation and Maintenance Plan shall be submitted with the Final Design Documents.

C. Cost Estimate

The Respondent shall develop cost estimates that are used to ensure that the facility has the financial resources necessary to construct and implement the corrective measure. The cost estimate developed in the Corrective Measure Study shall be refined to reflect the more detailed/accurate design plans and specifications being developed. The cost estimate shall include both capital and operation and maintenance costs. An Initial Cost Estimate shall be submitted simultaneously with the Prefinal Design submission and the Final Cost Estimate with the Final Design Document.

D. Project Schedule

The Respondent shall develop a Project Schedule for construction and implementation of the corrective measure or measures to identify when all critical path tasks begin and end. The Respondent shall identify specific dates for completion of the project and major interim milestones. An Initial Project Schedule shall be submitted simultaneously with the Prefinal Design Document, and the Final Project Schedule shall be submitted with the Final Design Document.

E. Construction Quality Assurance Objectives

The Respondent shall identify and document the objectives and framework for the development of a construction quality assurance program including, but not limited to responsibility and authority, personnel qualifications, inspection activities, sampling requirements, and documentation.

F. Health and Safety Plan

The Respondent shall modify the Health and Safety Plan developed for the facility investigation to address the activities to be performed at the facility to implement the corrective measure(s).

G. Design Phases

The design of the corrective measure(s) should include the following phases:

1. Preliminary design:

   The Respondent shall submit the Preliminary design when the design effort is approximately 30% complete. At this state the Respondent shall have field-verified the existing conditions of the facility. The preliminary design shall reflect a level of effort that addresses the technical requirements of the project so that they may be reviewed to determine if the final design will provide an operable and usable corrective measure. Supporting data and documentation shall be provided with the design documents defining the functional aspects of the program. The preliminary construction drawings by the Respondent shall be well organized and clearly presented. The scope of the technical specifications shall be outlined to reflect the final specifications. Each preliminary submission shall include a description of design bases and calculations required to develop the design.

2. Intermediate design:

   Complex project design may require review of the design documents between the preliminary and the prefinal/final design. At the discretion of the Navy, a design review may be required at 60% completion of the project. The intermediate design submittal should include the same elements as the prefinal design.

3. Correlating plans and specifications:

   General correlation between drawings and technical specifications is a basic requirement of any set of working construction plans and specifications. Before submitting the project specifications, the Respondent shall:

   a. Coordinate and cross-check the specifications and drawings; and

   b. Proof the edited specifications and cross-checks of all drawings and specifications.

These activities shall be completed prior to the 95% prefinal submittal to the Navy.

4. Equipment startup and operator training:

   The Respondent shall prepare contractor requirements and include them in the technical specifications governing treatment systems for providing appropriate service visits by experienced personnel to supervise the installation, adjustment, startup, and operation of the treatment systems, and training covering appropriate operational procedures once the startup has been accomplished.

5. Additional studies:

   CMI may require additional studies to supplement the available technical data. At the direction of the Navy for any such studies required, the Respondent shall furnish all services, including fieldwork as required, materials, supplies, plans, labor, equipment, investigations, studies, and superintendence. Sufficient sampling, testing, and analysis shall be performed to optimize the required treatment and/or disposal operations and systems. All principal personnel involved in the development of the program shall attend the initial meeting. The purpose will be to discuss objectives, resources, communication channels, the role of personnel involved, and orientation of the site, etc. The interim report shall present the results of the testing with the recommended treatment or disposal system (including options). A review conference shall be scheduled after the interim report has been reviewed by all interested parties. The final report of the testing shall include all data taken during the testing and a summary of the results of the studies.

6. Prefinal and final design:

   The Respondent shall submit the prefinal design documents at 95% completion of design, and after approval of the prefinal submission, the respondent shall incorporate the required revisions and submit the final design documents in the form of reproducible drawings, specifications, and plans and procedures.

   The prefinal design submittal shall consist of the Design Plans and Specifications, Operation and Maintenance Plan, Capital and Operating and Maintenance Cost Estimate, Project Schedule, Quality Assurance Plan, and Specifications for the Health and Safety Plan.

   The final design submittal shall consist of the Final Design Plans and Specifications (100% complete), the Respondent's Final Construction Cost Estimate, the Final Operation and Maintenance Plan, Final Quality Assurance Plan, Final Project Schedule, and Final Health and Safety Plan specifications. The quality of the design documents should be such that the Respondent could include them in a bid package and invite contractors to submit bids for the construction project.

TASK III: CORRECTIVE MEASURE CONSTRUCTION

Following approval of the final design, the Respondent shall develop and implement a construction quality assurance (CQA) program to ensure, with reasonable certainty, that the completed corrective measure(s) meets or exceeds all design criteria, plans, and specifications. The CQA plan is a facility-specific document that must be submitted to the Navy for approval prior to the start of construction. At a minimum, the CQA plan should include the elements summarized below. Upon approval of the CQA plan the Respondent shall construct and implement the corrective measures in accordance with the approved design, schedule, and CQA plan. The Respondent shall also implement the elements of the approved Operations and Maintenance Plan.

A. Responsibility and Authority

The responsibility and authority of all organizations (i.e. technical consultants, construction firms, etc.) and key personnel involved in the construction of the corrective measure shall be described fully in the CQA plan. The Respondent must identify a CQA officer and the necessary supporting inspection staff.

B. Construction Quality Assurance Personnel Qualifications

The qualifications of the CQA officer and supporting inspection personnel shall be presented in the CQA plan to demonstrate that they possess the training and experience necessary to fulfill their identified responsibilities.

C. Inspection Activities

The observations and tests used to monitor the construction and/or installation of the components for the corrective measure(s) shall be summarized in the CQA plan, including the scope and frequency of each type of inspection. Inspections shall verify compliance with all environmental requirements and include, but not be limited to, air quality and emissions monitoring records, waste disposal records (e.g., RCRA transportation manifests), etc. The inspection should ensure compliance with all health and safety procedures. In addition to oversight inspections, the Respondent shall conduct the following activities:

1. Preconstruction inspection and meeting

Conduct a preconstruction inspection and meeting to:

a. Review methods for documenting and reporting inspection data;

b. Review methods for distributing and storing documents and reports;

c. Review work area security and safety protocol;

d. Discuss any appropriate modifications of the construction quality/assurance plan to ensure that site-specific considerations are addressed; and

e. Conduct a site walk-around to verify that the design criteria, plans, and specifications are understood and to review material and equipment storage locations.

The preconstruction inspection and meeting shall be documented by a designated person and minutes should be transmitted to all parties.

2. Prefinal inspection

Upon preliminary project completion the Respondent shall notify the Navy of the prefinal inspection, which will consist of a walk-through inspection of the entire project site to determine whether the project is complete and consistent with the contract documents and the approved corrective measure. Any outstanding construction items discovered during the inspection will be identified and noted. Additionally, treatment equipment will be operationally tested by the Respondent, who will certify that the equipment has performed to meet the purpose and intent of the specifications. If deficiencies are revealed, retesting will take place. The prefinal inspection report should outline the outstanding construction items, actions required to resolve items, completion date for these items, and date for final inspection.

3. Final inspection

Upon completion of any outstanding construction items, the Respondent shall notify the Navy of the final inspection, which shall consist of another walk-through inspection of the project site. The prefinal inspection report shall be used as a checklist with the final inspection focusing on the outstanding construction items identified in the prefinal inspection. Confirmation shall be made that outstanding items have been resolved.

D. Sampling Requirements

The sampling activities, sample size, sample locations, frequency of testing, acceptance and projection criteria, and plans for correcting problems as addressed in the project specifications should be presented in the CQA plan.

E. Documentation

Reporting requirements for CQA activities shall be described in detail in the CQA plan. These include such items as daily summary reports, inspection data sheets, problem identification and corrective measures reports, design acceptance reports, and final documentation. Provisions for the final storage of all records also shall be presented in the CQA plan.

TASK IV: REPORTS

The Respondent shall prepare plans, specifications, and reports as set forth in Task I through Task IV to document the design, construction, operation, maintenance, and monitoring of the corrective measure. The documentation shall include, but not be limited to, the following:

A. <u>Progress</u>

The Respondent shall at a minimum provide the Navy with signed (monthly, bimonthly) progress reports during the design and construction phases and (semiannual) progress reports for operation and maintenance activities containing:

1. A description and estimate of the percentage of the CMI completed;

2. Summaries of all findings;

3. Summaries of all changes made in the CMI during the reporting period;

4. Summaries of all contacts with representatives of the local community, public interest groups, or State government during the reporting period;

5. Summaries of all problems or potential problems encountered during the reporting period;

6. Actions being taken to rectify problems;

7. Changes in personnel during the reporting period;

8. Projected work for the next reporting period; and

9. Copies of daily reports, inspection reports, laboratory monitoring data, etc.

B. <u>Draft</u>

1. The Respondent shall submit a draft CMI Program Plan as outlined in Task I;

2. The Respondent shall submit draft Construction Plans and Specifications, Design Reports, Cost Estimates, Schedules, Operation and Maintenance Plans, and Study Reports as outlined in Task II;

3. The Respondent shall submit a draft Construction Quality Assurance Program Plan and Documentation as outlined in Task III, and

4. At "completion" of project construction, the Respondent shall submit a CMI Report to the Navy documenting that the project is consistent with the design specifications, and that the corrective measure is performing adequately. The Report shall include, but not be limited to, the following:

   a. Synopsis of the corrective measure and certification of the design and constructions;

b. Explanation of any plan modifications and why these were necessary for the project;

c. Listing of the criteria, established before the corrective measure was initiated, for judging the functioning of the corrective measure and explaining any modification to these criteria;

d. Results of facility monitoring, indicating that the corrective measure will meet or exceed the performance criteria; and

e. Explanation of the operations and maintenance (including monitoring) to be undertaken at the facility.

This report should include all of the daily inspection summary reports, inspection summary reports, inspection data sheets, problem identification and corrective measure reports, block evaluation reports, photographic reporting data sheets, design engineers' acceptance reports, deviations from design and material specifications (with justifying documentation), and as-built drawings.

C. Final

The Respondent shall finalize the CMI Program Plan, Construction Plans and Specifications, Design Reports, Cost Estimates, Project Schedule, Operations and Maintenance Plan, Study Reports, Construction Quality Assurance Program Plan/ Documentation, and the CMI Report incorporating comments received on draft submissions.

(NOT ALL OF THE ITEMS LISTED BELOW MAY BE REQUIRED AT EACH FACILITY.)

Submission Summary

A summary of the information reporting requirements contained in the CMI Scope of Work is presented below:

Corrective Measure Implementation Information Reporting Requirements

Facility Submission	Due Date
Draft Program Plans (Task I)	[DATE]
Final Program Plans (Task I)	[NUMBER] of days after Navy comment on Draft Program Plans
Design Phases (Task II A)	
- Preliminary Design (30% completion)	[NUMBER] of days after submittal of Final Program Plan
- Intermediate Design (60% completion)	[NUMBER] of days after submittal of Final Program Plan
- Prefinal Design (95% completion)	[NUMBER] of days after submittal of Final Program Plan
- Final Design (100% completion)	[NUMBER] of days after submittal of Prefinal Design
(Task II B through G)	
- Draft Submittals	Concurrent with Prefinal Design
- Final Submittals	Concurrent with Final Design
Additional Studies: Interim Report (Task II F)	[DATE ESTABLISHED PRIOR TO FINAL DESIGN]
Additional Studies: Final Report (Task II F)	[NUMBER] of days after Navy comment on Interim Report
Draft Construction Quality Assurance Plan (Task III)	Prior to construction
Final Construction Quality Assurance Plan (Task III)	[NUMBER] of days after Navy comment on Draft Construction Quality Assurance Plan
Construction of Corrective Measure(s)	As approved in Final Design
Prefinal Inspection Report	[NUMBER] of days after Prefinal Inspection
Draft CMI Report (Task IV)	Upon completion of construction phase
Completion of Construction	As approved by Navy in the Corrective Measure Design
Final CMI Report (Task IV)	[NUMBER] of days after Navy comment on Draft CMI Report
Progress Reports for Tasks I through III	[MONTHLY, BIMONTHLY]
Progress Reports During Operation and Maintenance	[SEMIANNUAL]

APPENDIX B

GLOSSARY OF TERMS USED TO DESCRIBE BIOVENTING PRINCIPLES AND IMPLEMENTATION

acidity - measure of the hydrogen ion concentration of a solution

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

advection - process of transport of a fluid due to mass movement

aerated thickness - the vertical height of the in situ volume being supplied air by the bioventing system

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

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

AFCEE - Air Force Center for Environmental Excellence

alkalinity - measure of the hydroxide ion concentration of a solution

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

auger drilling - drilling by rotating a spiral channel supported on a center tube (hollow stem) or shaft (solid stem)

bentonite - clay composed from volcanic ash decomposition composed of montmorillonite and beidellite. Usually characterized by high swelling on wetting. Used to form seals in well boreholes and monitoring points

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

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

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

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

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

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

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

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

bioventing - the process of aerating subsurface soils by means of installed vents to stimulate in situ aerobic biological activity to optimize bioremediation while minimizing volatilization

blower - a unit of rotating mechanical equipment used to increase the pressure in a gas stream and providing a total pressure rise of more than 4 inches of water and less than 14.7 psi

BTEX - benzene, toluene, ethylbenzene, and xylenes

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

capillary fringe - the first layer of rock or soil above the saturated zone; a layer in which water is held by capillarity (lowest portion of the vadose zone)

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

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

CERCLA - Comprehensive Environmental Response, Compensation, and Liability Act

CFR - Code of Federal Regulations

CFU - colony-forming units (measuring the number of CFUs is a low-cost screening method to determine the ability of a contaminated matrix to sustain microbial action)

clay - fine-grained soil that can exhibit putty-like cohesive properties within a range of water content and which shows considerable strength when air-dry. Predominantly secondary mineral particles <0.002 mm (U.S. Department of Agriculture system).

CMI - Corrective Measure Implementation

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

CPT - cone penetrometer

CPVC - chlorinated polyvinyl chloride

CQA - construction quality assurance

CQC - construction quality control

CQM - construction quality management

DC - direct current

DFW - definable features of work

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

diffusivity - diffusion coefficient; the mass of material which diffuses across an area per unit time due to a unit concentration gradient (the value of the diffusivity depends on both the molecule diffusing and the medium it is moving through)

electron acceptor - a relatively oxidized compound that takes electrons from an electron donor during cellular respiration (oxygen is the final electron acceptor in aerobic biodegradation)

electron donor - reduced organic or inorganic compound that gives electrons to an electron acceptor during cellular respiration

enzyme - biologically produced, protein-based catalyst

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

FID - flame ionization detector

FPT - female pipe thread

free product - organic contaminant existing as a separate liquid phase

GC - gas chromatograph

grout - cement or similar material suspended in water to form a mixture that is fluid when prepared but that hydrates to form a rock-like solid

h - aerated thickness

HASP - health and safety plan

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

Henry's law constant - the partial pressure exerted by a compound divided by the concentration of the compound in aqueous solution. The Henry's law constant of low-solubility compounds can be approximated as the ratio of the pure component vapor pressure and the water solubility.

ICE - internal combustion engine

in situ - a treatment process that can be carried out within the site of contamination without bulk excavation

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

k_o - oxygen use rate

LEL - lower explosive limit

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

MS - mass spectrometer

nutrients - constituents required to support life and growth

O&M - operations and maintenance

off-gas - air, possibly containing contaminant vapors which leaves a process, typically from a point source during extraction operations

OSHA - Occupational Safety and Health Administration

OSWER - Office of Solid Waste and Emergency Response

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

oxygen use rate - rate of reduction of oxygen concentration due to biological and chemical action (used to determine respiration rate when the chemical oxygen demand is negligible)

permeability - measure of the capacity of a rock, soil, or sediment to allow passage of liquid or gas through pores without damage to the structure of the media

pH - a numerical designation of the acidity and alkalinity; technically, the pH is the negative of the logarithm of the hydrogen ion concentration; a pH of 7.0 indicates a neutral condition, that is, an exact balance of hydrogen ion and hydroxide ion concentration; values between 7 and 14 indicate an alkaline condition, and values between 7 and 0 indicate an acidic condition

PID - photoionization detector

pipe schedule - standard method for designating the wall thickness of pipe

pore space - the open space and minute passages in a solid material

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

PPE - polypropylene

ppmv - part per million by volume (indicates vapor concentration)

pressure drop - pressure difference between two points in a flowing system caused by frictional resistance to the fluid flow

PVC - polyvinyl chloride

PVDF - polyvinylidene fluoride

Q_s - total airflow rate required to aerate a contaminated volume

Q_w - airflow rate into (or out of) a vent well

QA/QC - quality assurance/quality control

radius of influence - the maximum radial extent of in situ pressure or airflow changes occurring due to an air extraction or injection well

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

RCRA - Resource Conservation and Recovery Act

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

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

respiration - oxidation of compounds to provide energy for cells

respiration rate - rate of reduction of oxygen concentration due to biological action

R_I - radius of influence

RI/FS - remedial investigation/feasibility study

rotameter - a device to measure flowrate using a shaped weight in a tapered tube

rotasonic drilling - drilling by rotating and vibrating a hollow tube sand - unconsolidated rock and mineral particles with diameters ranging from 0.05 to 2 mm

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

scfm - standard cubic feet per minute

short-circuiting - undesirable condition in which air passes into or out of a vent well through the well seal

silt - unconsolidated rock and mineral particles with diameters ranging from 0.002 to 0.05 mm

smear zone - in situ volume where contaminants have been spread above and below the water table due to fluctuations of the water-table level

soil gas permeability - a soil's capacity to allow gas flow. The gas permeability varies according to grain size, soil uniformity, porosity, and moisture content

soil type - system of classification of soils based on physical properties

soil vapor extraction - a process designed and operated to maximize the volatilization of low-molecular-weight compounds, with some biodegradation occurring

SOW - scope of work

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

SVE - soil vapor extraction

SVOC - semivolatile organic compound

TPH - total petroleum hydrocarbons

treatability - a measure of the effectiveness of a process option for remediating a contaminated site

tremie pipe - a large diameter pipe with a hopper at the top end used to place fill or grout into a borehole annulus

UCL - upper confidence limit

USACE - U.S. Army Corps of Engineers

UV - ultraviolet

V - volume of contaminated soil

vacuum-enhanced pumping - use of a vacuum pump to lift groundwater, or other liquids or gases, from a well while producing a reduced pressure in the well vadose zone - the zone of soil below the surface and above the permanent water table, where liquids are usually immobile and sorbed to soil particles and gases predominate in the soil pores

vapor pressure - the pressure exerted by a single component phase at a given temperature

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

VOC - volatile organic compound

volatile - easily vaporized at relatively low temperatures

volatilization - process of vaporizing a liquid into a gas

water table - planar surface between the vadose zone and the saturated zone