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Natural Pressure-Driven Passive Bioventing

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ACRONYMS AND ABBREVIATIONS

AFB	Air Force Base
AFCEE	Air Force Center for Environmental Excellence
AFS	Air Force Station
bgs	below ground surface
BVCE	Bioventing Cost Estimator
CBC	Construction Battalion Center
cfd	cubic feet per day
cfm	cubic feet per minute
CO_2	carbon dioxide
DoD	Department of Defense
DOE	Department of Energy
ESTCP	Environmental Security Technology Certification Program
FRTR	Federal Remediation Technologies Roundtable
ID	inside diameter
MCAS	Marine Corps Air Station
NAPL	nonaqueous-phase liquid
NAS	Naval Air Station
NAWC	Naval Air Warfare Center
NFESC	Naval Facilities Engineering Service Center
NRC	National Research Council
NSY	Naval Ship Yard
O&M	operation and maintenance
ORP	oxidation-reduction potential
O_2	oxygen
Pa	pascal
Parsons ES	Parsons Engineering Science
PFFA	Petroleum, Oils, and Lubricants Fuel Farm Area
ppmv	part(s) per million by volume
PVC	polyvinyl chloride
RCRA	Resource Conservation and Recovery Act
SAIC	Science Applications International Corporation
SVE	soil vapor extraction

TKN	total Kjeldahl nitrogen
TPHg	total petroleum hydrocarbons as gasoline
TPH-Jet A	total petroleum hydrocarbons as jet propulsion fuel A
TPH-JP4	total petroleum hydrocarbons as jet propulsion fuel #4
U.S. EPA	United States Environmental Protection Agency
UST	underground storage tank
VMP	vapor monitoring point
WBS	work breakdown structure

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- Dr. Robert Hinchee, of Battelle Memorial Institute, provided key insights and overall guidance on finding and evaluating a suitable demonstration site and demonstration design, and in interpreting the demonstration results.

- Michael Phelps, from Parsons Engineering Science, found the demonstration site (Castle Airport) and was responsible for implementing the passive bioventing system and designing the remote data acquisition system.

- Jim Gonzales, of the Air Force Center for Environmental Excellence (AFCEE), provided access to Castle Airport and postponed startup of a conventional bioventing system to accommodate the passive bioventing demonstration.

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- Jed Costanza, of NFESC, and Dr. Joseph Rossabi, of Westinghouse Savannah River Company, performed short-term measurements of airflow at potential DoD demonstration sites and provided assistance with the demonstration design and with the interpretation of results.

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1.0 EXECUTIVE SUMMARY

Bioventing is a process of aerating soils to stimulate in situ aerobic microbial activity and promote the bioremediation of water-unsaturated soils that have been contaminated with nonchlorinated hydrocarbons. Passive bioventing utilizes the gas pressure difference that develops between the atmosphere and the subsurface to drive air into the subsurface through vent wells. Conventional bioventing systems use at least one powered blower to inject air into the subsurface. This document provides information needed for comparing passive bioventing to conventional bioventing on the basis of performance, installation and operating costs, and implementation issues. The primary demonstration objective was to identify a site where passive bioventing would be successful. The secondary objective was to measure the rate of airflow and radius of oxygen influence as the result of operating a pilot-scale passive bioventing system that consisted of one vent well with a one-way passive valve and soil-gas monitoring points.

Passive bioventing has been successfully demonstrated at four sites where the depth to groundwater is greater than 100 feet. This demonstration focused on determining if passive bioventing could be successfully applied at sites where the depth to groundwater is less than 100 feet. A search for suitable shallow groundwater sites where passive bioventing could be successfully applied was conducted by evaluating site documentation and performing field measurements. A total of 15 Department of Defense (DoD) sites located throughout the contiguous United States were identified as having features that could potentially lead to the successful application of passive bioventing. Short-term measurements were completed at each of the 15 sites, and passive bioventing was found to be feasible at three of the 15 sites based on measured rates of natural airflow into pre-existing vent wells of at least 1 cubic foot per minute (cfm). New vent wells were installed at two of the sites with negligible airflow rates to determine if the poor rates were caused by improperly constructed and screened wells. The new airflow rates remained below the criteria (>1 cfm or >1,200 cubic feet per day [cfd], and >10 ft radius of oxygen influence per vent well) established to indicate the potential for a successful passive bioventing application. Airflow rates measured in wells at Castle Airport (formerly Castle Air Force Base [AFB]) in Merced County, California, indicated the potential for a successful demonstration of passive bioventing. A demonstration-scale passive bioventing system was installed at Castle Airport and its performance was monitored over a period of 6 months. The details of the demonstration are described in a technology evaluation report (Parsons Engineering Science [Parsons ES], 1999).

Although the cleanup goals for water-unsaturated or vadose zone soils contaminated with nonchlorinated hydrocarbons vary from state to state and locally within states, bioventing has been accepted by regulatory agencies in all 10 United States Environmental Protection Agency (U.S. EPA) regions and in 30 states (U.S. EPA, 1994a). Most hydrocarbon contaminants are mixtures (e.g., gasoline or diesel fuel) that contain both volatile and semivolatile hydrocarbon fractions. The U.S. EPA has designated soil vapor extraction (SVE) as the presumptive remedy for soils contaminated with volatile organic compounds (U.S. EPA, 1996). Bioventing stimulates microbial activity, which results in the degradation of both volatile and semivolatile hydrocarbons via biotic growth and metabolism, whereas SVE removes only volatile compounds. The U.S. Air Force Center for Environmental Excellence (AFCEE) Technology Transfer Division advocates the use of bioventing over SVE for fuel-contaminated soils.

The volume of air driven into the subsurface by the demonstration-scale passive bioventing system at Castle Airport reached a daily maximum of 9,433 cfd, with an average air injection rate of 3,409 cfd over a 53-day period. Peak daily airflow rates ranged from 5.1 to 15 cfm and primarily occurred each day before noon. The radius of oxygen influence in the subsurface at Castle Airport after the 7-week demonstration was estimated to be 42 feet. For comparison, the conventional bioventing system located at Castle Airport operates at 35 cfm, or approximately 50,000 cfd, and has a radius of pressure influence of 100 feet.

The primary advantage of passive bioventing over conventional bioventing is eliminating the need for an electrically powered blower. At many DoD facilities such as ranges, training, and proving grounds, electrical power is either unavailable or would be expensive to obtain. Even at facilities where access to electrical power is available, contaminated sites often are not conveniently located near electrical power. Passive bioventing also can be used to deliver oxygen at a rate equal to the biological demand once conventional bioventing has been used to establish a significant radius of oxygen influence.

The primary disadvantage of passive bioventing is that it is viable only at sites with suitable subsurface conditions that lead to a sustained difference between atmospheric and subsurface gas pressure. The passively induced airflow rate is generally lower in magnitude than the airflow produced by conventional bioventing systems using electrically powered blowers. A lower rate of airflow or oxygen delivery into the subsurface will result in a smaller radius of oxygen influence and the need for more vent wells. Also, in some cases, passive bioventing may require significant additional remediation time.

A cost comparison between the installation and operation of a full-scale passive bioventing and a conventional bioventing system at Castle Airport suggests that the passive system would save approximately $31,300. This cost saving would be significantly greater if electricity were not already available at the site to operate electric blowers for a conventional bioventing system.

2.0 TECHNOLOGY DESCRIPTION

Passive bioventing uses the difference between atmospheric and subsurface gas pressure to drive ambient air through vent wells into water-unsaturated soil. The pressure difference is a result of the subsurface gas pressure trying to equilibrate to changing atmospheric pressure. Oxygen in the ambient air is used by resident aerobic microorganisms to potentially transform hydrocarbon contaminants in situ into byproducts of microbial respiration. Passive bioventing uses the delay in equilibration between atmospheric and subsurface gas pressure to harness energy and promote airflow into a vent well, replacing the electrically powered blower normally used in conventional bioventing.

2.1 TECHNOLOGY BACKGROUND

Bioventing is a process of injecting ambient air into water-unsaturated soils to promote the in situ bioremediation of petroleum hydrocarbon contaminants. The minimum requirements for successful application of bioventing include adequate soil-gas permeability, adequate soil-water content, suitable microbial population, and adequate control of the contaminant vapor plume (U.S. EPA, 1994b; Leeson and Hinchee, 1997). Delivery of oxygen into soils has been shown in controlled laboratory studies to accelerate the microbial metabolism of hydrocarbons to nontoxic byproducts, including carbon dioxide (CO_2) and water, and increase microbial mass (National Research Council [NRC], 1993). Bioventing is applicable at sites where the subsurface is contaminated with aerobically biodegradable compounds, including most of the constituents found in gasoline, jet fuel, diesel fuel, and many other petroleum-based products (U.S. EPA, 1995a). Bioventing is not applicable for most chlorinated solvents (e.g., tetrachloroethylene) or other halogenated compounds (e.g., polychlorinated biphenyls).

A subsurface gas-phase oxygen (O_2) concentration of less than 5% indicates that supplying oxygen through the injection of ambient air will stimulate resident aerobic microorganisms (Leeson and Hinchee, 1997). The rate of air injection is a balance between supplying sufficient oxygen to meet microbial metabolic requirements and minimizing the spread of volatile hydrocarbon contaminants (e.g., benzene) to areas outside the treatment zone. Bioventing does not rely significantly on volatilization of soil contaminants to achieve cleanup goals because contaminants are degraded in situ within water-unsaturated soil.

Conventional bioventing requires at least one electrically powered blower to inject ambient air into or extract soil gas from the subsurface. Extracting soil gas will potentially draw ambient air into the subsurface. A regenerative electric blower normally is used to inject air into contaminated soil via vent wells that are screened above the water table in water-unsaturated soils. Electric blowers usually inject air at 15 to 40 cfm, or 20,000 to 50,000 cfd. Low injection pressures of 10 to 30 inches of water (2,500 to 7,500 Pa) minimize the spread of volatile hydrocarbons while maximizing the rate of biodegradation. Conventional bioventing has been successfully demonstrated at DoD and other facilities (Miller et al., 1993; Leeson and Hinchee, 1997). Conventional bioventing is included in the list of treatment technologies profiled in the *Remediation Technologies Screening Matrix and Reference Guide* (Federal Remediation Technologies Roundtable [FRTR], 2002).

Passive bioventing uses the gas pressure difference that develops between the atmosphere and the subsurface to drive air into the subsurface through vent wells. Previous field tests have shown that changes in atmospheric or barometric pressure cause vent wells screened in water-unsaturated soil to inhale and exhale air, a process sometimes termed "barometric pumping" or "breathing" (Pirkle et al., 1992 and Rossabi et al., 1993). During times of increasing barometric pressure, a positive pressure difference between the atmosphere and the subsurface exists, and air flows through the vent well into the subsurface (Figure 1). Air will flow from the subsurface through the vent well and into the atmosphere when barometric pressure is decreasing with time. The magnitude of the ensuing airflow rate is primarily a function of the rate of barometric pressure change, well screen depth and length, and the air permeability of the soil (Zimmerman et al., 1997; Rossabi and Falta, 2000).

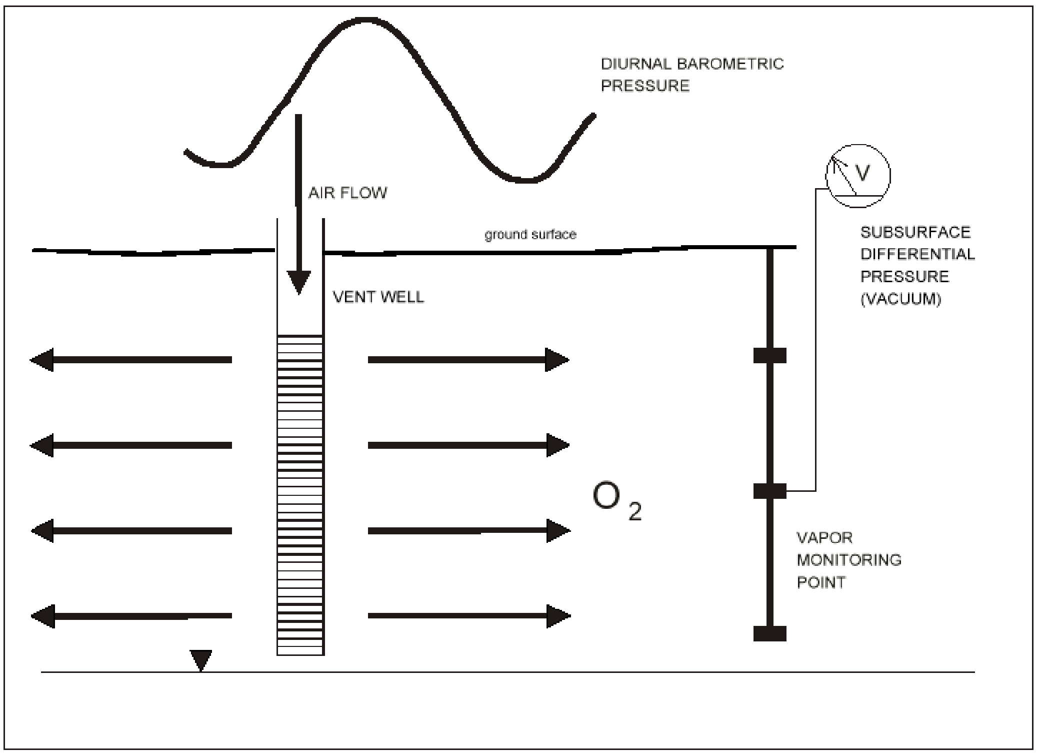

Figure 1. Air Inhalation During Passive Bioventing.

Daily (diurnal) barometric pressure normally reaches a minimum in the afternoon and a maximum in the early morning. Weather front (long-term) barometric pressure changes typically last 3 to 5 days and can be significant (Neeper, 2002). The difference between the diurnal barometric pressure from day to night is on the order of 3 inches of water (750 Pa). The passage of periodic weather fronts often causes an even greater change in barometric pressure with time. However, a significant change in barometric pressure is not sufficient to guarantee that air will flow between the atmosphere and the subsurface. Specific subsurface lithologic and stratigraphic conditions also must exist for any change in barometric pressure to induce significant airflow through vent wells. Barometric pressure-induced airflow has been measured at sites with vent wells screened in air-permeable, contaminated soils isolated from the atmosphere by more than 100 feet of water-unsaturated soil (Rossabi et al., 1993; Hoeppel et al., 1995). Airflow through vent wells screened in shallow, air-permeable contaminated soils isolated from the atmosphere by a layer of low air permeability also has been measured (Costanza and Rossabi, 2001). A thick (e.g., >100-foot) soil layer of high air permeability or a thinner soil layer of low air permeability can retard the flow of air between the atmosphere and subsurface, leading to a gas pressure difference. Although the magnitude of this naturally occurring pressure difference is low, being about 0.06 to 0.5 inch of water (15 to 125 Pa), the rate of barometric pressure-driven airflow through vent wells can range from 0.5 to more than 50 cfm (Riha, 2001).

2.2 PREVIOUS TESTING OF PASSIVE BIOVENTING

Passive bioventing has been demonstrated at two DoD and two Department of Energy (DOE) facilities in the contiguous United States (Table 1). These demonstrations were located in regions where the depth to groundwater was greater than 100 feet, and contaminants were located in air-permeable soils with low water content.

Table 1. Previous Passive Bioventing Demonstrations.

Location	Depth to Water (feet below ground surface [bgs])	Peak Airflow Rate (cfm)	Reference
Twentynine Palms, CA	200	7	Zimmerman et al., 1997
Hill AFB, UT	100	5	Battelle, 1995
Hanford, WA	200	20	Ellerd et al., 1999
Savannah River site, SC	120	20	Rossabi et al., 1993

2.3 IDENTIFICATION OF SUITABLE PASSIVE BIOVENTING SITE

Passive bioventing requires the presence of aerobically biodegradable hydrocarbons, located in air-permeable soil, with low gas-phase oxygen content and sufficient soil water content. Soil air permeability, which is a function of both soil type and water content, should be greater than 10^{-1} or 0.1 darcy ($\sim 1 \times 10^{-9}$ cm^2) to allow for the exchange of air in the air-filled soil pores (U.S. EPA, 1994b; Leeson and Hinchee, 1997). Soil air permeability should be measured rather than estimated from soil type because the range of intrinsic permeability for each soil type varies over several orders of magnitude (Table 2). Intrinsic permeability is a measure of the ease with which a fluid (i.e., air or water) is transported through soil subject to a pressure gradient. In general, clean sands (without silt or clay) and gravel are soils with an intrinsic permeability greater than 0.1 darcy and are therefore most suitable for passive bioventing.

Aerobic microorganisms require water to be present in the contaminated soil to support metabolic processes, including the degradation of hydrocarbons. A minimal soil water content of 2% by weight in sand was shown to adequately support in situ respiration (Leeson and Hinchee, 1997). However, as soil water content increases, there is a decrease in soil air permeability because of water obstructing the air-filled pore spaces. For example, Stylianou and DeVantier (1995) measured a 90% reduction in the air permeability of clean sand caused by an increase in water content from 5.1 to 21.8% by weight. Decreasing soil air permeability will

Table 2. Representative Soil Type and Range of Intrinsic Permeability.

Soil Type	Intrinsic Permeability (darcy)	
	Upper Value	Lower Value
Clay	10^{-5}	10^{-8}
Glacial till	10^{-1}	10^{-7}
Silt	1	10^{-4}
Silty sand	10^{2}	10^{-2}
Clean sand	10^{3}	10^{-1}
Gravel	10^{5}	10^{2}

Source: Freeze and Cherry, 1979

limit the rate of airflow into the subsurface, which will limit the supply of oxygen and result in a decrease in the rate of in situ respiration.

2.4 PILOT TEST

Once a suitable site is identified, the installation of a vent well and vapor monitoring points (VMP) is recommended to determine the rate of passively induced airflow, radius of oxygen influence, and in situ respiration rate to be used for the design of a full-scale system. As with conventional bioventing systems, soil VMPs are required to monitor passive bioventing performance. The VMPs are often spaced radially around the vent well at distances expected to be under the influence of the vent well. The concentration of oxygen, carbon dioxide, and volatile contaminants is measured in vapor samples collected from the VMPs to determine the radius of oxygen influence and treatment volume. The in situ respiration rate is determined by closing the vent well and measuring the decrease in oxygen at the VMPs over time.

Construction of the vent well and VMPs is accomplished using traditional groundwater monitoring well installation procedures, with the exception that the screened portion of the well is located in the contaminated, water-unsaturated subsurface. Vent wells and VMPs may be installed using a variety of drilling or direct-push techniques. However, appropriate placement and sizing of the screened intervals and proper well development are vital for effective vent well operation.

2.5 MEASUREMENT OF PASSIVE BIOVENTING AIRFLOW

Once the vent well and monitoring points are installed, the rate of airflow and oxygen influence can then be determined. Measuring passively induced airflow requires the use of an instrument that minimizes pressure loss. Although passively induced flows may be in the 5 to 20 cfm range, the airflow results from a relatively small pressure difference (15 to 150 Pa), unlike conventional bioventing. Many common airflow measurement devices introduce a pressure drop that will block or reduce passively induced airflow.

Several types of flow meters may be appropriate for measuring passive flow, including thermal anemometers, sonic and ultrasound techniques, vane anemometers, and soap bubble meters. The proper selection of an airflow meter is dependent on many factors, including airflow magnitude; desired measurement accuracy, sensitivity, and precision; and environmental conditions at the site. Thermal anemometers (e.g., TSI model 8475) often are selected because of their high sensitivity, large flow rate measurement range, and minimal pressure loss.

2.6 PASSIVE BIOVENTING SYSTEM DESIGN

Design of a passive bioventing system is similar to the design of a conventional bioventing system. For a comprehensive conventional bioventing design document, see the Air Force's *Bioventing Design Tool* (AFCEE, 1996) and the corresponding *Bioventing Cost Estimator* (NFESC, 1996). The passive bioventing system does not require an electric blower but does utilize a one-way passive airflow valve (see Figure 2 and picture on report cover page). The one-way passive valve is used to allow the passage of air into the vent well when the subsurface pressure is lower than atmospheric pressure. The valve closes when the subsurface pressure is greater than atmospheric pressure, preventing the exhalation of inhaled atmospheric oxygen and volatile contaminants from the subsurface. The operation of the one-way valve results in an expanding subsurface treatment volume through successive, passively induced, air injection events.

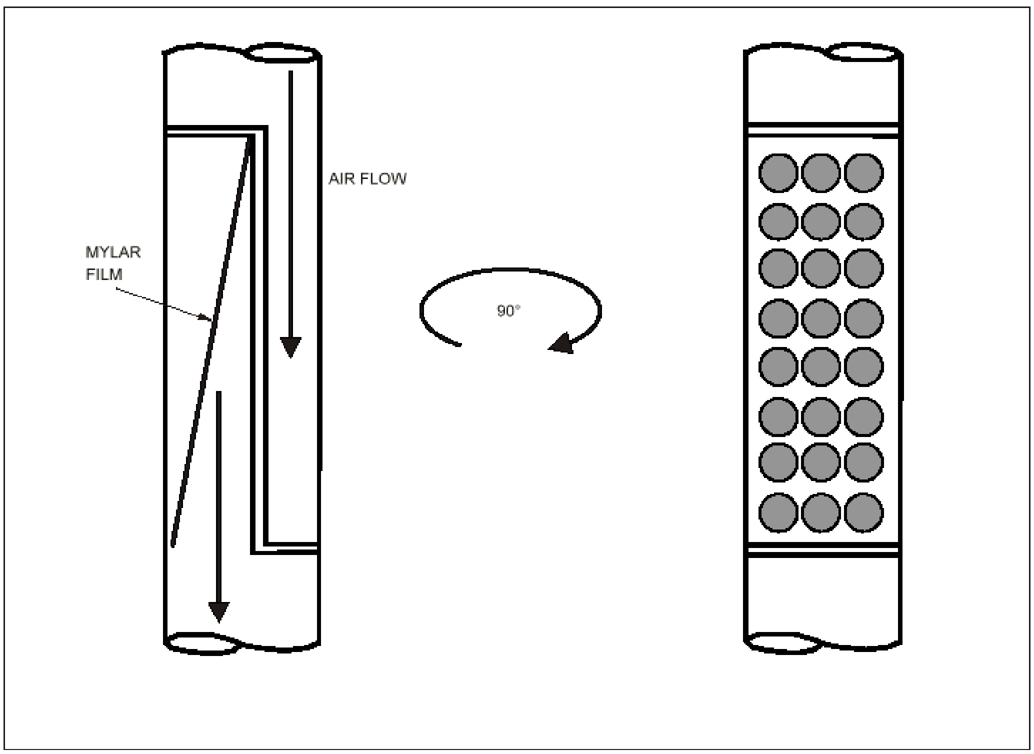

Figure 2. One-Way Passive Valve.

The number and spacing of the additional vent wells needed for a full-scale passive bioventing system are based on the rate of airflow and radius of oxygen influence determined from the single vent well and VMPs used in the pilot test (see Section 2.4). This scale-up procedure is identical to that employed for conventional bioventing system design. Manifold or piping systems may be used to link multiple vent wells to a single one-way passive valve as long as the piping system does not introduce a significant pressure loss.

The key design criterion for a passive bioventing system is the spacing of vent wells. The cost of installing many closely spaced vent wells, which might be required to achieve adequate subsurface oxygen distribution, would reduce the cost savings realized by eliminating the electric blower. The radius of oxygen influence and airflow are primarily a function of the following site characteristics.

- Effective air permeability of the contaminated soil (function of soil water content)
- Oxygen utilization rate of microorganisms (in situ respiration rate)
- Pressure difference between the atmosphere and contaminated subsurface

The oxygen utilization rate of microorganisms is affected by the following.

- Soil temperature
- Natural and contaminant organic carbon content
- Biodegradation rate of natural and contaminant organic compounds
- Soil pH
- Nutrient balance

Potential enhancements to passive bioventing design include using a tandem series of multiple vent wells and one-way valves in different configurations, where some vent wells are used for air injection and others are used for air extraction. In such a tandem arrangement, airflow could be directed to specific subsurface regions or underneath buildings.

2.7 LONG-TERM OPERATION

Long-term operation and maintenance (O&M) of a passive bioventing system involves periodically checking the operation of the one-way passive valve to ensure proper sealing when closed and easy opening during inflow pressure events. Periodic monitoring of the subsurface oxygen and contaminant gas content also should be performed to demonstrate adequate subsurface aeration and reduction in hydrocarbon content.

2.8 ADVANTAGES AND DISADVANTAGES

Passive bioventing shares many of the same advantages and disadvantages as conventional bioventing. Features specifically pertinent to passive bioventing are in **bold print**.

Advantages of passive (and conventional) bioventing include:

- **Eliminates the need for electrical lines and outlets**
- **Avoids the use of an electric blower and associated O&M costs**
- **Eliminates the need for a vacuum manifold system and associated trenching costs**
- **Low pressure air injection minimizes volatile contaminant transport to receptors**
- Applicable to both the volatile and semivolatile fractions of hydrocarbon fuel mixtures
- Uses ambient air without pretreatment
- No aboveground off-gas treatment

- Uses resident aerobic microbes for treatment
- Uses conventional, readily available supplies and construction techniques
- Minimal O&M requirements

Disadvantages of passive (and conventional) bioventing include:

- **Passive bioventing may require more vent wells than conventional systems**
- **Permeable soils with high moisture levels may have limited airflow**
- Presence of low air permeability soils greatly limits or prevents oxygen transport
- Extremely low water content soils (e.g., <2% by weight) may limit microbial degradation
- Significant separate phase hydrocarbon fluid may inhibit microbial degradation
- Preferential pathways (sand layers/fractures) can impede airflow to contaminant zones
- Chlorinated hydrocarbons, not biodegraded aerobically, may be mobilized
- Requires thorough subsurface characterization, including soil air permeability testing
- Multiple years may be required to achieve cleanup goals

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3.0 DEMONSTRATION DESIGN

This section describes the demonstration objectives, demonstration site selection efforts, and the installation of a demonstration-scale passive bioventing system at Castle Airport.

3.1 PERFORMANCE OBJECTIVES

Three primary performance objectives were established for this demonstration project, including:

- Identifying a suitable passive bioventing site
- Installing a vent well, VMPs, and measuring key design parameters
- Comparing the installation and operation costs estimated for a full-scale passive bioventing system to the estimated costs for a full-scale conventional bioventing system

A successful passive bioventing system supplies a sufficient amount of oxygen to maintain the subsurface gas-phase oxygen content at greater than 5% without using an excessive number of vent wells. The numerical goals used to indicate technical and economic success of passive bioventing included:

- Measurement of peak airflow rate of at least 1 cfm per well or total daily airflow rate of at least 1,200 cfd per well
- Radius of oxygen influence of at least 10 feet per vent well

The radius of oxygen influence was chosen to provide a minimum vent well spacing of 20 feet, which makes passive bioventing cost-effective when compared with conventional bioventing. The airflow rate of 1 cfm represents the minimum airflow required to meet an in situ respiration rate of 0.2% O_2/hr in a contaminated subsurface volume with a radius of 10 feet and depth of 15 feet. A radius of oxygen influence of 10 feet, a contaminated thickness of 15 feet, and air-filled porosity of 0.25 represent an air-filled pore volume of approximately 1,200 cubic feet. While the U.S. EPA (1995a) recommends an air exchange between 0.25 and 0.5 pore volumes per day for sufficient oxygen supply, a more conservative rate of 1 pore volume of air exchange per day was chosen for this project (1,200 cfd).

3.2 SELECTION OF DEMONSTRATION SITE

The process of identifying and selecting a suitable passive bioventing demonstration site was split into two steps. Step 1 involved reviewing documents (e.g., remedial investigation reports) that describe subsurface conditions and contaminants at DoD sites throughout the contiguous United States. Step 2 consisted of measuring airflow in exisiting groundwater monitoring wells at selected sites. The document review process consisted specifically of evaluating historical data from DoD sites for the presence of a contaminated air-permeable soil layer that appears to be isolated from the atmosphere by a layer of low air permeability. Of the sites reviewed, 15 had conditions that were deemed favorable for passive bioventing. The rate of passively induced airflow into existing groundwater monitoring wells at each of the 15 sites was then measured over a 2-week period to determine if peak airflow was greater than 1 cfm. The site selection process was conducted in two phases, with Phase I focused on sites in the western United States and Phase II expanded to sites in the eastern United States. Table 3 lists the 15 DoD installations (five Navy, seven Air Force, and three Army) and where each site is located, as well as the measured peak airflow rate, soil lithology and stratigraphy, and depth to groundwater.

Table 3. Summary of the Airflow Measured in Existing Monitoring Wells.

	DoD Installation (Name, State)	Measured Peak Airflow (cfm)	Lithology/Stratigraphy	Depth to Groundwater (feet bgs)
Phase I	Construction Battalion Center (CBC) Port Hueneme, CA	0.11	Silty sand	10
	McClellan AFB, CA	<0.01	Silt over sand	60 (seasonal: 30-70)
	Naval Air Warfare Center (NAWC) China Lake, CA	0.08	Clay over silty sand	60
	Maxwell AFB, AL	0.10	Clay over sand	24
	Castle Airport, CA	15.00	Silt over sand	60 (seasonal: 10-70)
Phase II	MacDill AFB, FL	0.25	Asphalt over silty sand	5
	Marine Corps Air Station (MCAS) Beaufort, SC	0.18	Silty sand	10
	Fort Stewart, GA	0.40	Concrete over silty sand	11.5
	Robins AFB, GA	0.33	Silty sand	8
	Finland Air Force Station (AFS), MN	30.00	Fractured rock	60 (seasonal: 10-60)
	Fort Jackson, SC	0.23	Silty and clayey sand	9-19
	Fort Riley, KS	0.60	Clayey silt over sand	28
	Tinker AFB, OK	1.20	Clay over silty sand	30
	Naval Ship Yard (NSY) Philadelphia, PA	0.23	Asphalt over sand	4
	Naval Air Station (NAS) Weymouth, MA	0.43	Glacial till	7

At eight of the 15 sites, groundwater was within 15 feet of the ground surface and silty sand was the predominant water-unsaturated soil type. Two of the 15 sites (MacDill AFB and NSY Philadelphia), were covered with asphalt and one site (Fort Stewart) was covered with concrete. Hydrocarbon-contaminated sand was overlain by a lower permeability soil (e.g., clay or silt) at six of the 15 sites (McClellan AFB, NAWC China Lake, Maxwell AFB, Castle Airport, Fort Riley, and Tinker AFB). Fractured rock contaminated with chlorinated solvents made up the subsurface conditions at the former Finland AFS. Chlorinated solvents were also the predominant contaminant at the Tinker AFB site. Airflow at each site was measured using an air velocity transducer (TSI model 8475) installed into a 2-inch diameter polyvinyl chloride (PVC) pipe section that was attached to the top of each existing monitoring well. The air velocity transducer was powered by a 12V battery that was recharged by two 10W solar panels. A HERMIT 3000 data logger was used to record air velocity, barometric pressure, and air temperature at 15-minute intervals for a period of 14 days. Of the 15 sites, three had passively induced peak airflow rates greater than 1 cfm: Castle Airport, Tinker AFB, and Finland AFS.

With the exception of the well located at Tinker AFB, none of the wells used to measure the peak airflow rate (Step 2) was designed for airflow. Groundwater monitoring wells typically are constructed with well screens that extend only a short distance above the water table, into water-unsaturated soil. Fort Stewart and Robins AFB had subsurface soil conditions that were potentially favorable for passive bioventing, but the groundwater monitoring well screen sections at these two sites only extended into the capillary fringe where the air-filled porosity was limited. The presence of significant water in the pore spaces could prevent or limit the amount of air that could flow into the subsurface, given the small barometric pressure driving force encountered during passive bioventing. Vent wells were installed at Fort Stewart and at Robins AFB to evaluate the potential of using wells designed to maximize airflow. However, the peak airflow rate measured in the vent wells at Fort Stewart and Robins AFB was less than 1 cfm. The low airflow rate at Fort Stewart was attributed to low soil air permeability. Soil boring logs completed during the Resource Conservation and Recovery Act (RCRA) Facility Investigation Report (Science Applications International Corporation [SAIC], 2000) indicated the presence of a potentially air-permeable pebble layer between 11 and 13 feet bgs. A pebble layer, which consisted of a clay matrix surrounding the pebbles, was encountered during installation of the vent well, rendering this layer low in air permeability. The low airflow rate at Robins AFB was attributed to the rapid, unrestricted movement of air through the shallow unsaturated subsurface soils, which impeded airflow through the vent well. Further details on the Fort Stewart and Robins AFB efforts can be found in the *Technology Demonstration Plan, Site-Specific Addendum* (Battelle, 2002).

No pilot-scale demonstration was completed in the eastern United States because airflow rates reater than 1 cfm were not measured except at Tinker AFB and Finland AFS. Because no petroleum contaminants—only chlorinated solvents (which are not amenable to aerobic biodegradation)—were present at Tinker AFB and Finland AFS, passive bioventing would have required modifications to an SVE system. Passive SVE was deemed outside the scope of this project. The airflow rate measured at Castle Airport (Step 2 of Phase I) was above the 1 cfm threshold, so a pilot-scale passive bioventing system was installed and a demonstration conducted. The following sections describe the design and installation of the passive bioventing system at Castle Airport.

3.3 DEMONSTRATION SITE/FACILITY CHARACTERISTICS

Castle Airport, formerly Castle AFB, is located in Merced County, California, approximately 5 miles northwest of the city of Merced (Figure 3). Castle AFB was selected for closure under the Defense Base Closure and Realignment Act of 1990 and was officially closed in September of 1995.

The Petroleum, Oils, and Lubricants Fuel Farm Area (PFFA), built in the 1940s, is located in the southern portion of the Main Base Sector and was the bulk fuel storage and distribution facility for Castle AFB. Approximately 18 underground storage tanks (UST) were located at PFFA and four above ground storage tanks (3 million gallon total capacity) are currently located at PFFA. Soil and groundwater contamination, primarily petroleum hydrocarbons from surface spills, leaking USTs, and fuel distribution lines, were identified during the remedial investigation stage (Jacobs, 1995). Most of the PFFA is paved with asphalt or concrete, or is covered with gravel.

Figure 3. Castle Airport Location.

Detailed site data are provided in the *Technology Demonstration Plan, Site-Specific Addendum* (Parsons ES, 1998a). The potential for passive bioventing at PFFA was discovered during the completion of a conventional bioventing pilot test (Parsons ES, 1998b). During air permeability testing, the field scientist noted that changes in barometric pressure were clearly affecting the pressure measurements used to infer radius of influence. The passive bioventing demonstration was completed before the installation and operation of the full-scale conventional bioventing system.

3.3.1 Nature and Extent of Contamination

Remedial investigations have identified soil and groundwater contamination at PFFA (Jacobs, 1995). The soil is impacted with residual petroleum hydrocarbon contamination; and the groundwater is contaminated with both petroleum hydrocarbons and chlorinated solvents. However, nonaqueous-phase liquids (NAPL) have not been observed in wells at PFFA. Soil and soil vapor sample analysis results indicate contamination is greatest in soils below 30 feet bgs, and extends to groundwater.

The maximum detected concentrations of contaminants in soil were:

- 28,000 mg/kg total petroleum hydrocarbons as gasoline (TPHg)
- 4,400 mg/kg TPH as jet propulsion fuel #4 (TPH-JP4)

- 2,880 mg/kg TPH as jet propulsion fuel A (TPH-Jet A)

- 12 mg/kg benzene, 80 mg/kg toluene, 40 mg/kg ethylbenzene, and 180 mg/kg total xylenes.

The maximum detected concentrations of contaminants in soil vapor were:

- 54,000 parts per million by volume (ppmv) TPHg

- 1,200 ppmv benzene, 820 ppmv toluene, 210 ppmv ethylbenzene, and 700 ppmv total xylenes.

Soil gas was analyzed at two uncontaminated background locations (PFFAVMP01 and MW270) located approximately 1,300 feet southeast (upgradient) of the contaminated area. Subsurface oxygen concentrations at these locations were above 19.0%, indicating that there is little natural oxygen demand in the soil and that any measure of oxygen depletion in the contaminated area is an indication of microbial activity associated with the petroleum hydrocarbon contamination.

3.3.2 Geology

The shallow subsurface stratigraphy at PFFA is characterized by Holocene to Pleistocene alluvial deposits consisting of interbedded sequences of sands, silts, and gravels. These deposits include the Riverbank and Modesto formations. Groundwater was generally first encountered at approximately 50 to 70 feet bgs during the demonstration, although historically groundwater was as shallow as 10 feet bgs in some areas. Groundwater pumping is extensive in the areas surrounding Castle Airport.

A generalized cross section of the demonstration area is shown in Figure 4. The subsurface in the upper 20 feet consists predominantly of silty sand overlying a laterally continuous clay/silt layer (greater than 90% silt/clay and 25.5% water by weight) located between approximately 20 and 25 feet bgs. This low permeability layer impedes the equalization of barometric pressure between the atmosphere and the air-permeable contaminated soils located beneath 25 feet bgs, resulting in airflow through vent wells screened below 25 feet bgs. Between 30 and 35 feet bgs, there is petroleum hydrocarbon-impacted sand (58% coarse and 26% fine sand by weight) with little to no fines. The sand located between 30 and 35 feet is underlain by another continuous clay/silt layer (19±2% water by weight) that is approximately 5 to 10 feet in thickness. Below this second clay/silt layer, sand extends to the groundwater table. The water content of the contaminated sands was between 2% and 10% by weight, a range considered optimal for bioventing, with sufficient moisture for microorganisms, but not high enough to limit air permeability (U.S. EPA, 1995a). Measured soil pH values were between 7.30 and 8.13 within the range considered optimal for microbial activity. Background oxygen concentrations indicate that natural organic compounds in the soils do not create a significant oxygen demand.

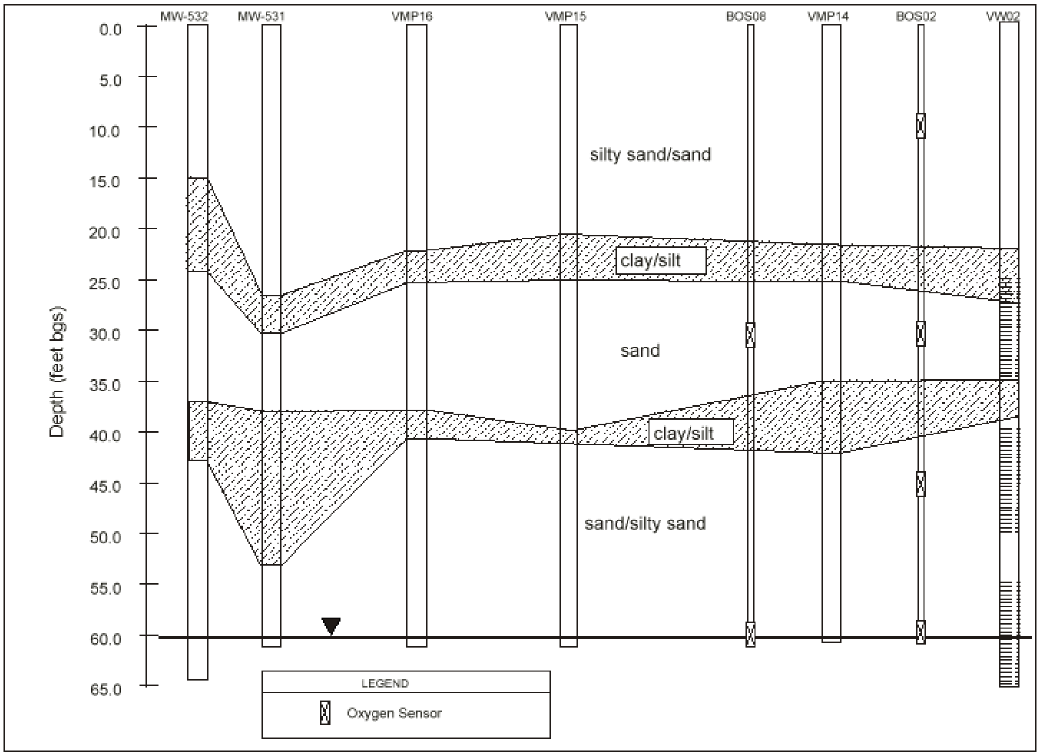

Figure 4. Castle Airport Geologic Cross-Section.

Oxidation-reduction potential (ORP) and microbially reducible iron also were measured for selected soil samples. These measurements are not part of standard bioventing protocols; however, highly reduced soils and significant concentrations of reduced iron could potentially result in significant oxygen demand and increase the oxygen delivery requirements for a passive system. ORP was between 164 and 206 mV and reducible iron was between the laboratory detection limit (2.0 mg/kg) and 44 mg/kg. Reducible iron concentrations were higher in the samples collected from 45 feet bgs, where soil contaminant concentrations also were highest. This indicated the potential that a portion of the measured oxygen utilization rate was due to the oxidation of iron. However, the reducible iron concentrations were significantly less than the contaminant concentrations at 45 feet bgs and, based on stoichiometry, would result in an oxygen demand far less than that required for microbial breakdown of the contaminants.

3.3.3 Soil Air Permeability

Soil air permeability was determined in the demonstration area during a conventional bioventing pilot test (Parsons ES, 1998b). The test consisted of injecting air into monitoring well MW-531 that was screened in the coarser-grained materials below 25 feet bgs (Figure 4). Air permeability of the sand below 25 feet bgs was between 38 and 200 darcies (0.38 to 2×10^{-6} cm^2), and the radius of pressure influence was determined to be 110 feet using a conventional blower. The air permeability is within the range considered suitable for bioventing (U.S. EPA, 1995a).

3.3.4 Climate

The climate of central California, where Castle Airport is located, is characterized by wet winters and long dry summers with high temperatures often exceeding 100° F. The mean annual temperature at Castle Airport is 62° F; the mean monthly temperatures range from 45° F in February to 79° F in July. During the summer, the clear, dry air allows for rapid heating near the ground surface, leading to large differences between day and night temperatures (frequently 40° F or more). The mean annual precipitation is 12 inches. Winds from the northwest prevail throughout most of the year. Although the strongest winds occur between January and March, daily peak wind speeds typically are between 10 and 20 miles per hour throughout most of the year.

3.4 PHYSICAL SETUP/OPERATION

The initial phase of the demonstration was conducted in March 1998 and consisted of installing one vent well (VW02). The vent well was installed using hollow-stem auger techniques and was constructed of 4-inch inside diameter (ID) Schedule 40 PVC casing and 0.04-inch slotted screen. The vent well was screened between 25 and 65 feet bgs, below the near-surface silty sand and clay/silt layer (Figure 4). The vent well was constructed with three isolated 10-foot screened sections that were used to evaluate airflow rates into the three different lithologic zones. A section of solid PVC casing and a bentonite seal isolated the screened sections. Airflow was measured through each of the screened sections. A total of eight VMPs were installed along two straight line transects from the vent well at radial distances of 4, 8, 12, and 16 feet. Each VMP was constructed using a buried oxygen sensor with an integrated sampling and pressure measurement port (Model XTM253SP, Datawrite Research Corp., Visalia, California) strapped to 2-inch ID solid PVC casing running the length of the borehole. Each sensor was isolated at depth using bentonite seals between the sensor and sand filter packs. A one-way passive valve was constructed and used during testing to enhance the radius of oxygen influence. The valve was constructed of 4-inch ID clear PVC (Nisei Plastics, Oakland, California). Initially, a single-celled foam rubber was used as the material for the valve. However, test results indicated that some air leakage was occurring. A Mylar® sheet subsequently was substituted for the foam rubber and used for the remainder of the demonstration tests.

The demonstration was conducted over a 6-month period (starting in late April 1998 and continuing through late October 1998) following installation of the vent well, VMPs/directly-buried sensors, and the data acquisition system. Six tests were conducted. Test 1 was designed to evaluate the effects of barometric pressure fluctuations on subsurface oxygen, and pressure conditions without any system enhancement. Test 2 was designed to establish a radius of influence without the use of the one-way passive valve. Test 3 was designed to collect in situ respiration data and allow subsurface oxygen concentrations to be depleted prior to the initiation of Test 4. Test 4 evaluated the effect of the one-way passive valve on the radius of oxygen influence. Tests 5 and 6 were based on an analysis of the data from Test 2, which indicated the occurrence of a significant weather-front-related event and, therefore, was not comparable to the other tests. Table 4 presents the timing and purpose of each test.

Table 4. Test Configurations and Dates.

Test Name	Test Configuration	Dates
TEST 1	Vent well closed (control)	30 Apr - 13 Jun
TEST 2	Vent well open, without one-way passive valve	14 Jun - 02 Jul
TEST 3	Vent well closed (measure in situ respiration rate)	02 Jul - 15 Jul
TEST 4	Vent well open, with one-way passive valve installed	16 Jul - 06 Sep
TEST 5	Vent well closed (measure in situ respiration rate)	06 Sep - 03 Oct
TEST 6	Vent well open, without one-way passive valve; repeat of TEST 2	03 Oct - 30 Oct

3.5 MONITORING PROCEDURES

The number of samples required to monitor the changes in barometric and subsurface conditions justifies the investment in dedicated sensors and use of data loggers. Multiple data loggers (HERMIT 3000, In-Situ, Inc., Laramie, Wyoming) were used to record measurements at 10-minute intervals from the following sensors.

- Barometric pressure (internal to the HERMIT 3000 datalogger)
- Airflow rate (Model 8475, TSI Inc., St. Paul, Minnesota)
- Atmosphere-to-subsurface differential pressure at each VMP (607-3B, Dwyer Instruments, Inc., Chicago, Illinois)
- Subsurface oxygen concentration at each VMP (Model XTM253SP, Datawrite Research Corp., Visalia, California)
- Ambient air temperature (K-type thermocouple)
- Groundwater elevation (miniTROLL, In-Situ, Inc., Laramie, Wyoming)

Details of the monitoring system can be found in the following documents.

- Final Technology Demonstration Plan (Revision 2), Natural Pressure-Driven Passive Bioventing (Parsons ES, 1997)
- Technology Demonstration Plan, Site-Specific Addendum, Natural Pressure-Driven Passive Bioventing (Parsons ES, 1998a)
- Natural Pressure-Driven Passive Bioventing Demonstration Report (Parsons ES, 1999)

3.6 ANALYTICAL PROCEDURES

The analytical measurements and associated methods are summarized in Table 5.

Table 5. Analytical Procedures.

Media	Analyte	Method
Soil organic and water content	Total petroleum hydrocarbons	EPA 8015M/8015B
	Volatile organic compounds	EPA 8020A/8260
	Soil water content	ASTM 2216
Soil inorganic and physical properties	Available nitrogen - TKN	E351.4M
	Total phosphorus	E365.3M
	Alkalinity	E310.1M
	Total iron	E6010A
	Microbially reducible iron	Lovley & Phillips, 1987
	Soluble iron	DIWET/E6010A
	ORP	ASTM D1498- 76
	pH	E9045C
	Grain-size analysis	ASTM D422
Soil vapor sampling	Petroleum hydrocarbons	EPA TO-3
	Total volatile hydrocarbons	Field instrument
	Oxygen	Field instrument
	Carbon dioxide	Field instrument

TKN = total Kjeldahl nitrogen

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4.0 PERFORMANCE ASSESSMENT

The performance of passive bioventing at the Castle Airport PFFA site was determined by measuring the rate of airflow and radius of oxygen influence resulting from operating the demonstration-scale passive bioventing system. The passive bioventing system consisted of a single vent well and eight soil VMPs used for periodic soil-gas measurements. The measured radius of oxygen influence was used to determine the vent well spacing that would be required for a full-scale passive bioventing system at PFFA.

Figure 5 shows the hourly barometric and subsurface gas pressure and the gas pressure difference (barometric – subsurface) and the induced rate of airflow in vent well VW02 that was measured during a 4-day period (Test 4) at Castle Airport. Small differences between barometric and subsurface gas pressure, on the order of 0.3 inch of water (75 Pa), led to airflow into the subsurface on the order of 10 cfm. A positive airflow rate indicates that air was being inhaled into the subsurface through the vent well, whereas a negative airflow rate indicates that air was being exhaled from the subsurface through the vent well. Inhalation primarily occurred each day before noon; exhalation occurred in the afternoon. Test 4 was conducted with the one-way passive valve installed on the vent well, which allowed air to flow into the vent well and should have prevented the flow of air out of the vent well. The negative airflow rate that was caused by the negative gas pressure difference (subsurface > barometric) on July 31, 1998, and August 1, 1998, indicated that the passive valve was allowing air to leak out of the vent well in the afternoon during the exhalation cycle. The passive valve material was changed from foam rubber to a Mylar® sheet on August 2, 1998 (see Section 3.4), and the air leakage during the exhalation cycle was thereafter minimized.

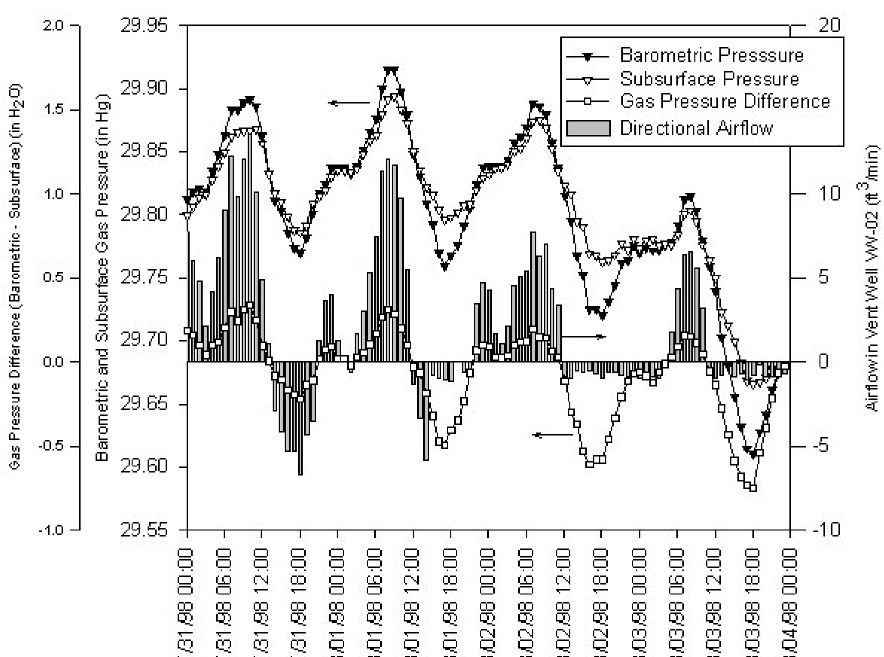

Figure 5. Barometric Pressure, Subsurface Pressure, Gas Pressure Difference, and Airflow Through Vent Well with One-Way Passive Valve (Test 4) at Castle Airport.

4.1 AIRFLOW AND RADIUS OF OXYGEN INFLUENCE

The daily total airflow rate ranged from a minimum of −1.8 cfd to a maximum of 9,433 cfd, with an average daily airflow rate of 3,409 cfd (Figure 6). Daily peak airflow rates ranged from 5.1 cfm to 15 cfm and occurred each day primarily before noon (Figure 5). The concentration of oxygen at a distance of 16 feet from the vent well (VW02) increased from less than 1% to approximately 12% in a period of 6 days, and continued to increase despite the daily variation in the amount of airflow. These results exceeded the stated numerical performance objectives of 1 cfm peak airflow, 1,200 cfd total daily airflow, and a radius of oxygen influence greater than 10 feet (Section 3.1).

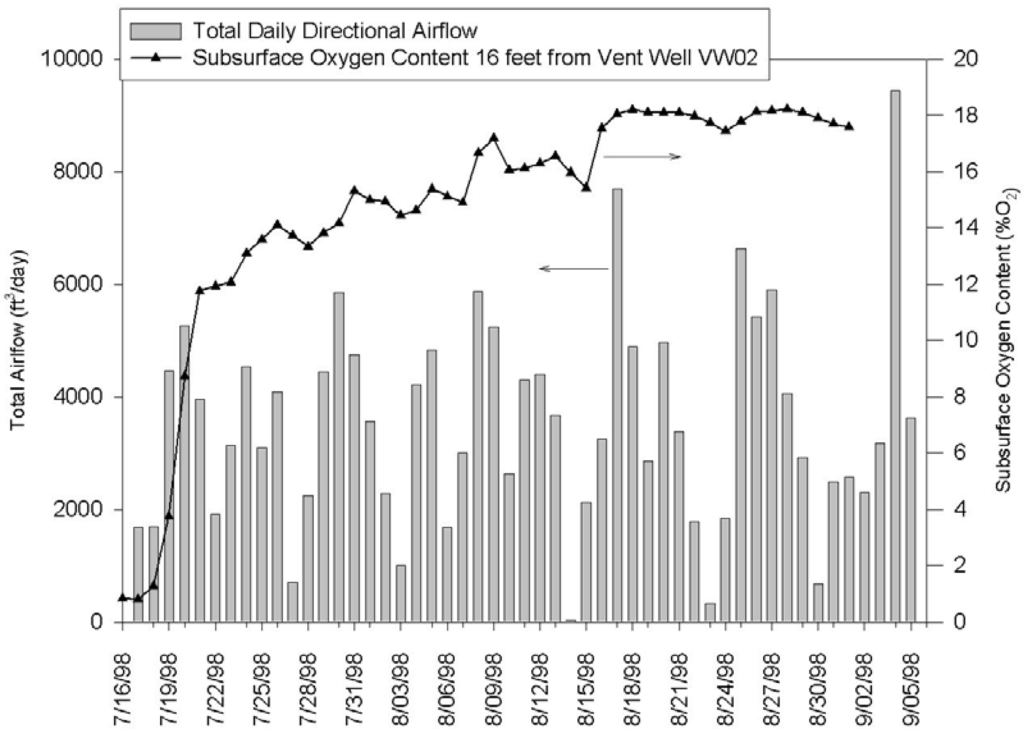

Figure 6. Total Airflow and Subsurface Oxygen Content with the One-Way Passive Valve for Hydrocarbon-Contaminated Sand 30 to 35 feet bgs at Castle Airport.

Subsurface oxygen at a VMP located 42 feet from the vent well increased from less than 1% to 5.5% after 49 days of passive bioventing. Because 5% oxygen in soil gas often is used as the minimum concentration of oxygen required to sustain aerobic conditions, this result suggests that the passive bioventing radius of oxygen influence was approximately 42 feet. The soil air permeability test for a conventional bioventing system at PFFA resulted in a radius of pressure influence of 110 feet (Section 3.3.3). This result was considered to represent the radius of oxygen influence for a conventional bioventing system, even though no oxygen measurements were completed (Parsons ES, 1998b).

4.2 EFFECT OF THE ONE-WAY PASSIVE VALVE

The airflow and subsurface oxygen concentration results shown in Figure 6 were obtained with the vent well fitted with a one-way passive valve (Figure 2). Two separate tests were performed to evaluate passive bioventing effectiveness without the one-way passive valve (Tests 2 and 6). Without the one-way valve (Test 2), the daily total airflow rate ranged from a maximum exhalation of −22,275 cfd to a maximum inhalation of 23,190 cfd, with an average daily airflow rate of −707 cfd (Figure 7). A negative airflow rate in Figure 7 indicates that air was flowing from the subsurface to the atmosphere, whereas a positive airflow rate indicates airflow from the atmosphere into the subsurface. The very high airflow rates obtained during the first three days of Test 2 were thought to be caused by the passage of a weather front. The concentration of oxygen at a distance of 16 feet from the vent well (VW02) increased from less than 1% to approximately 12% in a period of 4 days, but fluctuated in response to the variation in airflow.

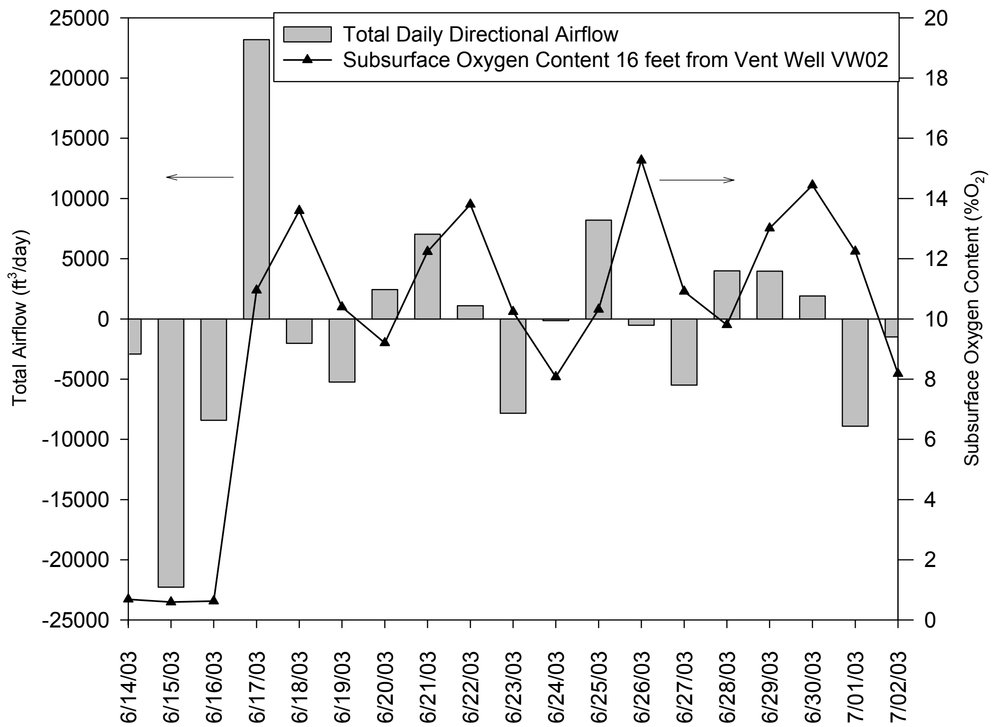

Figure 7. Total Airflow and Subsurface Oxygen Content Without the One-Way Passive Valve for Hydrocarbon-Contaminated Sand 30 to 35 feet bgs at Castle Airport.

4.3 IN SITU OXYGEN UTILIZATION RATE

The in situ oxygen utilization rate was determined by closing the vent well (VW02) and measuring the decline in subsurface oxygen concentration in the VMPs with time. The average decline of oxygen was 1.0% O_2/day.

4.4 PREDICTION OF OXYGEN RADIUS OF INFLUENCE

A simple analytical approach was developed to predict the radius of oxygen influence given the measured airflow, oxygen utilization rate, and an estimate of the air-filled porosity and thickness of the treatment zone. The analysis was based on a plug flow reactor model with a zero-order reaction (Weber and DiGiano, 1996) and yields the following equation:

$$r = \sqrt{\frac{Q\left(C_{in} - C_{\min}\right)}{\pi b \theta_a k_O}} \tag{1}$$

where r is the radius of oxygen influence (feet), Q is the average airflow per day (3,409 ft^3/day), C_{in} is the concentration of oxygen injected into the subsurface (21% O_2), C_{min} is the minimum concentration of oxygen required to sustain aerobic conditions (5% O_2), b is the thickness of the aerated zone (35 feet), θ_a is the air-filled porosity (0.27 volume air/volume total), and k_O is the measured oxygen utilization rate (1.0% O_2/day). Equation 1 predicts that, at a distance of 43 feet from the vent well, the oxygen concentration will be 5% at PFFA. Although this simple approach did yield a result that was similar to the measured radius of oxygen influence (42 feet), Equation 1 may not work for all subsurface conditions.

5.0 COST ASSESSMENT

The information included in this section provides an assessment of the expected installation and operation costs for a full-scale passive bioventing system. Costs for typical passive and conventional bioventing systems were categorized using the second-level work breakdown structure (WBS) coding system detailed in the *Guide to Documenting Cost and Performance for Remediation Projects* (U.S. EPA, 1995b). For comparison purposes, the expected costs are given for a single site of approximately the same size as the Castle Airport PFFA demonstration site, 115,000 square feet or 2.6 acres.

Costs were estimated using the *Bioventing Cost Estimator (BVCE) and User's Guide* (Naval Facilities Engineering Service Center [NFESC], 1996), experience from the *Bioventing Pilot Test Initiative* (Downey et al., 1994), and actual costs incurred during both conventional bioventing pilot testing and demonstration test activities at PFFA. The costs include the following activities:

- Data review
- Site visits and planning
- Work plan and report preparation
- Regulatory approval
- Equipment costs
- Initial soil vapor survey
- Pilot testing
- Analytical sampling costs
- Well installation
- Full-scale system installation
- Yearly O&M
- System abandonment

For comparison, costs were included for both a conventional bioventing system and a passive bioventing system for the same site. The *Bioventing Cost Estimator* calculated that the conventional bioventing system would require three vent wells, five VMPs (three for the pilot test and two additional VMPs for the full-scale system), and one 150-cfm blower to treat the site. An upgrade to the existing electrical system (i.e., new distribution panels and meters) was required for the blower system; however, electrical power was already available at the site. Trenching and asphalt surface repair would be required to install the blower manifold system, which distributes air to the vent wells.

The cost estimate for the passive bioventing system did not include a blower, electrical system upgrade, or trenching and surface repair; however, one-way passive valves were included. Although a radius of oxygen influence of about 42 feet was measured during the short-term passive bioventing demonstration at Castle Airport, a long-term radius of oxygen influence of 85 feet was used in the cost estimation. Based on an estimated long-term radius of oxygen influence of 85 feet, the *Bioventing Cost Estimator* calculated that the passive bioventing system would require six vent wells to treat the site. It was assumed that the number of VMPs would remain the same for both systems because the area treated was the same size. The time period from initial installation to closure sampling was estimated to be 3 years for both the conventional and passive bioventing systems, based on experience gained during the AFCEE Bioventing Initiative. Included in the O&M costs were the collection and analysis of samples from the VMPs, yearly in situ respiration tests, and travel costs. It was assumed that all other costs (e.g., work plans, administration, and regulatory oversight) would be the same for both systems.

As shown in Table 6, the estimated cost to install a full-scale passive bioventing system at Castle Airport is approximately $31,300 less than the estimated cost for a full-scale conventional bioventing system, even though the passive system requires twice as many vent wells to treat the same soil volume. With an adequate radius of influence, the cost for the additional vent wells for a passive bioventing system can more than offset the extra costs required for a conventional bioventing system (blower installation, electrical power modification, trenches and piping for the manifold system, and associated additional O&M costs). The total estimated cost for a passive bioventing system is approximately $366,000, with a unit cost of approximately $2.49 per cubic yard. The yearly power costs for the blower were estimated to be $5,000; the cost to install the trenching and piping at such a large asphalted site with many subsurface utilities was approximately $20,000. Passive bioventing becomes more economically favorable as the time to treat subsurface contamination increases due to the greater O&M costs for conventional bioventing.

The estimated time to site closure is based on a constant rate of oxygen utilization over the three-year period. A reduction in the oxygen utilization rate with time has been observed at sites undergoing conventional bioremediation (U.S. EPA, 1995a). A passively induced airflow may be sufficient to meet the lower oxygen utilization rate. In this case, the electrically powered blower could be replaced with a one-way passive valve, and the conventional bioventing system infrastructure (wells, piping, etc.) would be used for passive bioventing. This transition from conventional to passive bioventing could reduce treatment costs while sustaining the rate of remediation.

It should be emphasized that passive bioventing would be very economical, compared to conventional bioventing, at sites without nearby electrical power lines or where electrical power generation is not permitted or practical. Military ranges, combat training areas, and proving grounds are good candidate sites for the application of passive bioventing.

Table 6. Cost Comparison.

WBS	Description	Unit Cost ($)	Units	Passive Bioventing		Conventional Bioventing	
				Units	Cost ($)	Units	Cost ($)
TREATMENT COST ELEMENTS							
33-01	**Mobilization and Preparatory Work**						
	Design costs	34,553	each	1	34,553	1	34,553
	Work plans	66,916	each	1	66,916	1	66,916
	(2003 dollars) SUBTOTAL				101,469		101,469
33-02	**Monitoring, Sampling, Testing, and Analysis**						
	Sampling equipment	9,575	each	1	9,575	1	9,575
	Soil-gas survey	10,506	each	1	10,506	1	10,506
	Pilot test	31,571	each	1	31,571	1	31,571
	Soil analysis	127	sample	35	4,445	35	4,445
	Soil vapor analysis	158	sample	14	2,212	14	2,212
	(2003 dollars) SUBTOTAL				58,309		58,309
33-03	**Site Work**						
	Trenching	19	foot	0	0	850	16,150
	Electrical utilities	3,650	total	0	0	1	3,650
	(2003 dollars) SUBTOTAL				0		19,800
33-11	**Biological Treatment**						
	Passive valves	181	each	6	1,086	0	0
	Field instrument rental	2,141	total	1	2,141	1	2,141
	Blower system	5,064	each	0	0	1	5,064
	VW installation	7,234	each	5	36,170	2	14,468
	VMP installation	6,959	each	2	13,918	2	13,918
	(2003 dollars) SUBTOTAL				53,315		35,591
AFTER TREATMENT COST ELEMENTS							
33-21	**Demobilization**						
	Well abandonment	23	foot	715	16,445	520	11,960
	Closure soil sampling	103	sample	18	1,854	18	1,854
	Closure vapor sampling	178	sample	9	1,602	9	1,602
	Final report	68,428	each	1	68,428	1	68,428
	(2006 dollars) SUBTOTAL				88,329		83,844
33-9X	**Other Costs**						
	Contingency	32,000	each	1	32,000	1	32,000
	(2003 dollars) SUBTOTAL				32,000		32,000
O&M	**Operation and Maintenance Costs**						
	Yearly testing	15,000	year	2	32,448	2	32,448
	Electricity	5,000	year	0	0	3	16,873
	Repairs	5,000	year	0	0	3	16,873
	(Includes annual 4% inflation rate) SUBTOTAL				32,448		66,194
				TOTAL COST ($)	**365,870**		**397,207**
				COST PER CUBIC YARD TREATED ($/cubic yard)	**2.49**		**2.71**

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6.0 IMPLEMENTATION ISSUES

The original passive bioventing concept was to convert existing groundwater monitoring wells into vent wells. Although this idea was certainly cost-effective, it did not prove to be viable due to limitations in the construction of existing groundwater monitoring wells reviewed for this project. Most monitoring wells installed in unconfined or phreatic aquifers have a significant portion of their intake screen located above the water table to accommodate changes in water table elevation. Many times this “dry” portion of the well intake screen is in contact with soil that is nearly water saturated (capillary fringe). Soil in the capillary fringe has low effective air permeability.

6.1 COST OBSERVATIONS

In general, the point at which the cost to install additional vent wells under a passive bioventing approach offsets the blower capital and O&M costs under a conventional bioventing approach will be site-specific and dependent on the following.

- Differences in the radius of influence between conventional and passive bioventing
- Cost to install electric power
- Local electric power costs
- Drilling costs affected primarily by contamination depth, soil type, and location
- The time frame needed to achieve remedial goals

6.2 LESSONS LEARNED

The following lessons were learned during implementation of this demonstration.

1. <u>Limited applicability to shallow groundwater sites</u>. Three of the 15 DoD sites had a passively induced airflow rate greater than the 1 cfm criterion. Although groundwater monitoring wells were determined to be less than ideal to facilitate passively induced airflow, they did provide an indication of the potential airflow at each site. Soil pore water levels are often higher in shallow sediments overlying a shallow water table than in shallow sediments overlying a water table at greater depth. Higher pore water saturation corresponds to lower air permeability in these sediments and, therefore, to lower airflow rates.

2. <u>Measure soil air permeability</u>. Soil gas or air permeability is one of the key parameters determining the suitability of both passive and conventional bioventing. Using the soil type as indicated in soil boring logs to estimate the air permeability of soil is not recommended. In situ air permeability testing should be conducted using a field test method (Leeson and Hinchee, 1997).

3. <u>Passive valve construction</u>. The one-way passive valve was constructed originally using single-cell foam rubber for the internal valve material. However, the foam rubber did not perform as well as Mylar®. If the design shown in Figure 2 is used, Mylar® should be used for the valve material. In addition, users should note that there is a commercially

available, off-the-shelf passive valve called the BaroBall™ (Durham Geo Slope Indicator, Stone Mountain, Georgia) developed by Savannah River site researchers. The BaroBall™ valve was not evaluated or used during this demonstration.

4. Oxygen sensors. The buried oxygen sensors provided good quality data and were relatively simple to install using standard hollow-stem auger techniques. It is recommended that the sensors with the integrated pressure measurement and sampling port (as used during this demonstration) also be used for any future installations because they allow for soil vapor samples to be collected. These oxygen sensors may also be very cost-competitive at conventional bioventing sites because, with the use of a data logger, in situ respiration tests can be performed unattended.

5. Reduced iron and ORP. The potential for reduced iron or highly reduced soils to exert a significant oxygen demand was determined to be low at Castle Airport. However, it is recommended that these simple measurements be performed at bioventing sites to evaluate the role of abiotic oxygen consumption on the measured in situ respiration rate.

6.3 TRANSITION OF CONVENTIONAL BIOVENTING TO PASSIVE BIOVENTING

Petroleum hydrocarbon-contaminated sites often have undergone some degree of remediation. At sites where SVE or conventional bioventing systems are operating, there may be an opportunity to switch off the electrically powered blower and install a one-way passive valve. The point at which a transition from an active SVE or bioventing system to a passive system should be considered is indicated by a decrease in the rate of contaminant mass recovery for SVE systems and by a measured decrease in the in situ respiration rate for bioventing systems. When the rate of contaminant mass recovery or in situ respiration begins to decrease, passively driven airflow rates may be sufficient to sustain the remediation rate. Transitioning to passive bioventing could potentially lower the O&M costs while delivering adequate volumes of air to sustain remediation.

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