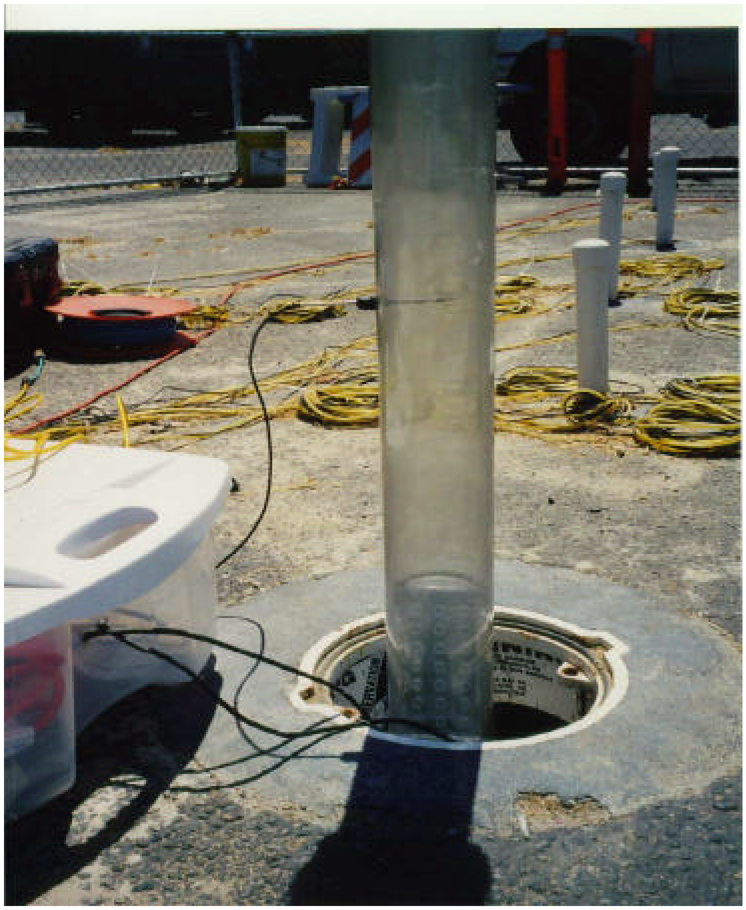
Cost and Performance Report
Natural Pressure-Driven Passive Bioventing



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Section 1: Executive Summary

This document summarizes the results from the demonstration of Natural Pressure-Driven Passive Bioventing at Castle Airport near Merced, California. Natural pressure-driven passive bioventing is not a new technology, but rather a new approach to conventional bioventing with one exception; the force generated by normal daily variation in atmospheric conditions or ocean tides replaces the powered blower in injecting air into the subsurface.

The results of the demonstration show that the daily airflow rates ranged from a minimum of 27 cubic fee per day (cfd) to a maximum of 9,300 cfd, with an average daily airflow rate of 3,400 cfd. It should be noted that the minimum daily air flow rate of 27 cfd was the only daily air flow rate less than 300 cfd throughout the entire seven week test period. Peak daily airflow rates ranged from 5.1 cubic feet per minute (cfm) to 15 cfm, although airflow rates near the daily peak airflow rate were rarely sustained for more than 30 minutes to an hour. The radius of influence after the seven-week demonstration was estimated to be potentially as high as 85 feet based on expected declining oxygen-utilization rates over time.

The conventional bioventing system that was installed at Castle Airport was operating at 35 cfm and had a radius of influence of 110 feet.

The primary advantage of passive bioventing over conventional bioventing or other remediation systems is elimination of the need for a blower and electrical power. At many facilities power is either unavailable or would be very expensive to obtain. Even at facilities where access to power is available, contaminated sites are often far away from power access points and operations and maintenance costs for the system are largely due to blower and power requirements.

The primary weakness of the passive technology is that adequate barometric pressure changes must take place in order for the required airflow rates and radii of influence to be achieved. Sites where these conditions would not be expected to exist include sites without significant barometric pressure changes, sites which have soils with very low air permeability (i.e., soils composed almost entirely of silt and clay), and sites with shallow groundwater and very limited lithologic stratification. At these sites, conventional bioventing or other remedial technologies would need to be applied.

A cost comparison between the installation of a full-scale passive bioventing and conventional bioventing system resulted in potential savings of $28,726 over a 5 year period. The cost comparison was made using the discounted cash flow method. While the passive bioventing approach may be less expensive it will require additional remediation time, estimated to be an additional year at Castle Airport.

Section 2: Technology Description

Natural pressure-driven passive bioventing is not a new technology, but rather a new approach to conventional bioventing. Conventional bioventing is a proven and cost-effective, *in-situ* biological treatment technology for removing aerobically biodegradable contaminants from unsaturated soil. Bioventing technology provides oxygen to natural, aerobic microorganisms that break down contaminants in vadose-zone soils.

Conventional bioventing requires at least one blower to either inject or extract air. Oxygen in ambient air is supplied to naturally occurring microorganisms that aerobically degrade the contaminants. A small, regenerative electric blower is usually used to inject air into contaminated soil via vent wells, which are screened above the water table. Relatively low airflow rates (on the order of 15 to 30 cfm per well [20,000 to 40,000 cubic feet per day (cfd) per well]) and low injection pressures (on the order of 10 to 30 inches of water) are used to minimize volatile organic compound loss while maximizing 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 technology profiles in the *Remediation Technologies Screening Matrix and Technology Guide* (USEPA, 1994).

Natural pressure-driven passive bioventing is essentially the same process with one exception; the force generated by normal daily variation in atmospheric conditions or ocean tides replaces the powered blower in injecting air into the subsurface.

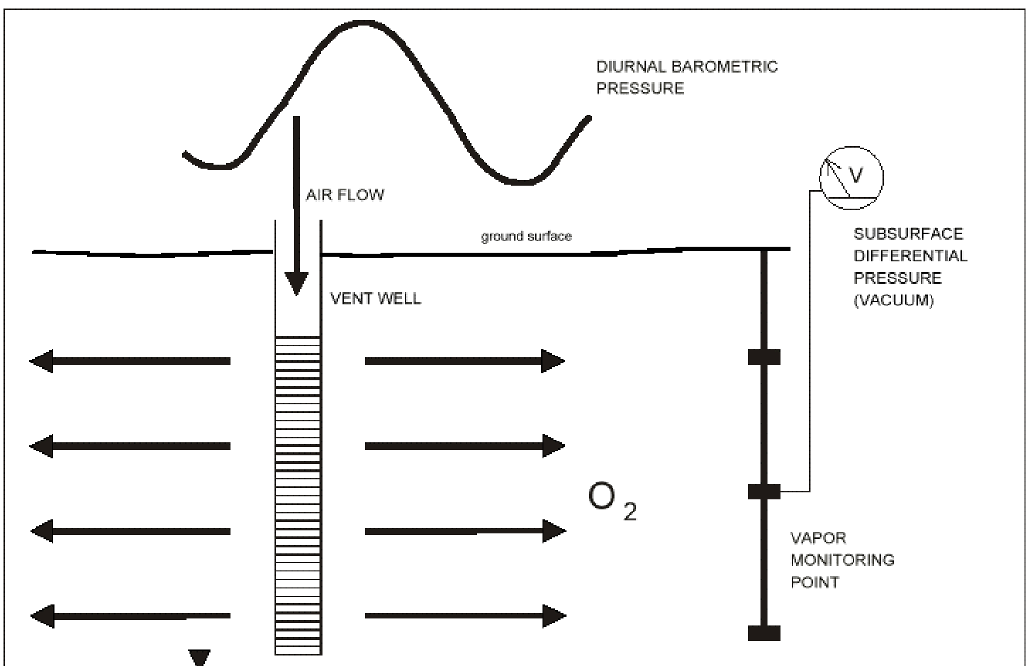


FIGURE 1

PASSIVE BIOVENTING PROCESS

\731272\REPORT\GRAPHICS\FIGS_L8A.CDR 1/11/99

Previous field tests have shown that changes in barometric pressure cause open vadose wells to inhale and exhale air (sometimes termed "barometric pumping" or "breathing") (Pirkle *et al.*, 1992; Rossabi *et al.*, 1993, Foor *et al.*, 1995; Zimmerman *et al.*, 1997). This phenomenon is illustrated on Figure 1. During times of increasing barometric pressure, a negative pressure gradient is developed between the atmosphere and the subsurface. Airflow can occur into vent wells or monitoring wells with screened portions located at depths where a significant difference between atmospheric and subsurface pressure exists. The reverse effect occurs during times of decreasing barometric pressure when a positive pressure gradient is developed and air flows out of the well.

The magnitude of the pressure gradient (which directly corresponds to the ensuing air flow rate) is primarily a function of the rate of barometric pressure change, well screen depth, soil air permeability, and soil porosity (Zimmerman *et al.*, 1997). These variables are manifested as a lag time between the changes in barometric pressure and the subsurface pressure, as well as a dampening in the magnitude of subsurface pressure change.

Barometric pressure varies inversely with daily air temperature, resulting in low pressures in the afternoon and high pressure in the early morning. Weather front (long-term) barometric pressure changes can also be significant. Typically barometric pressure varies diurnally on the order of approximately 0.2 inches Hg from day to night. The passage of periodic weather fronts can cause an even greater change in barometric pressure. However, a significant change in barometric pressure alone is not a sufficient guarantee that pressure gradients will actually be developed or can be engineered in the subsurface to create the airflow required.

2.1 Passive Bioventing Design. Design of a passive bioventing system is almost identical to the design of a conventional bioventing system. The difference results from replacing the electric blower and manifold system with one-way passive airflow valves (Figure 2) at each vent well. For a comprehensive conventional biovening design document, please see the Air Force's Bioventing Design Tool and the corresponding Bioventing Cost Estimator (NFESC, 1996).

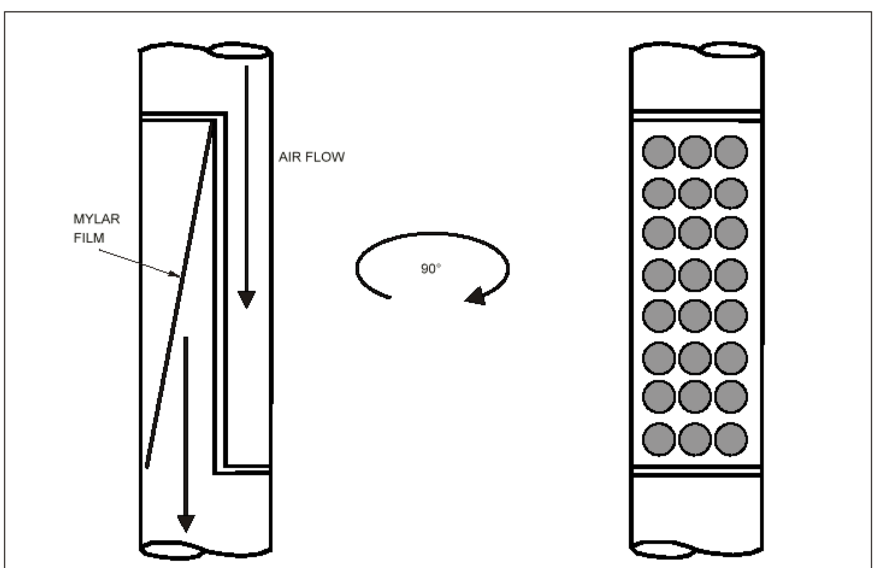


FIGURE 2
ONE-WAY, PASSIVE VALVE

In engineering or designing a passive bioventing system, the driving force for producing the required subsurface air exchange (or airflow) is provided by the pressure gradient between the atmosphere and the subsurface (Figure 1).

Using the one-way, passive valve, air can enter the vent well only when the inside well pressure is lower than atmospheric (due to barometric changes). When the reverse gradient occurs, the valve closes to prevent the exhalation of previously injected air. Because horizontal permeability is typically much greater than vertical permeability, through successive air injection events the treatment area expands as previously injected air moves outward from the vent well.

In addition to the vent wells used for air injection or extraction, soil vapor monitoring points (VMPs) are used to monitor system performance and are an important part of bioventing system design. The VMPs are spaced radially around the vent wells at distances expected to be under the influence of the vent wells (Figure 3). Oxygen, carbon dioxide, and contaminant concentration measurements are taken from vapor samples collected from the VMPs in order to determine the radius of influence and treatment area.

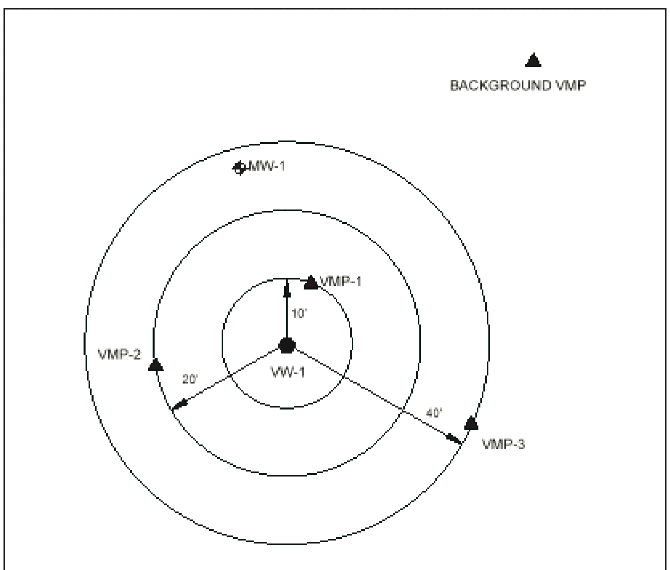


FIGURE 3
PLAN VIEW OF BIOVENTING WELL PLACEMENT (TYPICAL)

Potential enhancement to system designs 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 areas or underneath buildings.

2.2 Key Design Criteria. The key design criteria for passive bioventing systems is the calculated spacing for the vent wells, which is based on the expected radius of influence and the airflow rate. As the expected radius of influence and airflow rate decrease, a larger number of closely spaced vent wells are required to treat an area of contaminated soil. Eventually, the cost savings realized from not installing and operating a blower would be offset by the substantial increases in drilling and vent well installation costs if the radius of influence is small.

The expected radius of influence and airflow rate are primarily a function of the following site characteristics:

- magnitude of barometric pressure change;
- frequency of barometric pressure change;

- air permeability of the soil (a function of soil type, soil porosity, soil moisture); and,
- oxygen-utilization rate of microorganisms (*in-situ* respiration rate).

Other, less significant, factors which can affect biological respiration rates and, therefore, performance include:

- soil temperature;
- natural organic carbon content;
- soil pH; and,
- nutrient levels.

The presence of non-aqueous phase liquids may create vapor migration hazards and decrease the air permeability of the soil.

2.3 Advantages and Disadvantages. The major advantage of conventional bioventing over other remediation technologies is that it is a proven, cost-effective technology that promotes *in-situ* biodegradation of petroleum hydrocarbons in soil under a wide range of site conditions.

Bioventing has a widespread potential application because soil microorganisms are capable of degrading most petroleum products (including gasoline, jet-propulsion fuel, diesel fuel, and heating oils) under aerobic conditions. Bioventing technology has a particular advantage for soils contaminated with less volatile fuels since technologies that depend on volatilization, such as vapor extraction, are not very effective with these compounds.

The major weaknesses include that it can only be applied to vadose zone contamination amenable to aerobic biodegradation (e.g., petroleum hydrocarbons and chlorobenzenes), and its effectiveness is limited at sites with soil of low air permeability and moisture content (USEPA, 1994). The presence of preferential pathways, caused by stratification or other primary or second features in the subsurface can also cause limitations and performance problems. These problems include:

- Vertical preferential pathways, such as abrupt changes in lithology, deep root zones, or anthropomorphic features, could cause air flow to short circuit to the ground surface.

- Horizontal preferential pathways, such as higher permeability horizons, bedding planes, and anthropomorphic features, may inhibit remediation if they act to direct airflow away from or restrict airflow to contaminated zones.

The same weaknesses listed above for conventional bioventing also apply to passive bioventing.

The primary advantage of passive bioventing over conventional bioventing or other remediation systems is elimination of the need for a blower and electrical power. At many facilities power is either unavailable or would be very expensive to obtain. Even at facilities where access to power is available, contaminated sites are often far away from power access points and operations and maintenance (O&M) costs for the system are largely due to blower and power requirements.

If appropriately constructed (i.e., an adequate screened interval intersects the contaminated vadose zone soils), many existing monitoring wells (MWs) could be converted to passive bioventing wells by simply replacing their existing well caps with one-way, passive valves. Although this application of the technology may not work on all wells and not every contaminated site has a network of wells, given the very low cost, even a success rate of 1 in 5 or 10 sites would result in very low cost remediation.

The primary weakness of the passive technology is that adequate barometric pressure changes must take place in order for the required airflow rates and radii of influence to be achieved. Sites where these conditions would not be expected to exist include sites without significant barometric pressure changes, sites which have soils with very low air permeability (i.e., soils composed almost entirely of silt and clay), and sites with shallow groundwater and very limited lithologic stratification. At these sites, conventional bioventing or other remedial technologies would need to be applied.

Because the radius of influence and air flow rates for a passive system are likely to be lower than those for a conventional bioventing system, more vent wells will likely be required at most sites compared to a conventional bioventing system to achieve similar remediation times. However, if the system is designed to deliver an air flow rate that is able to meet microorganism oxygen demand, remediation times would not significantly increase with a passive bioventing system compared to a conventional bioventing system.

It may not be necessary to meet the maximum microbial oxygen demand at a site. It is expected that the radius of influence from a passive bioventing system would approach that of a conventional bioventing system over a relatively long time period. Although initially the radius of oxygen influence will be limited by the microbial demand near the vent well, as areas near the vent well are remediated and the oxygen demand is satisfied, the radius of influence should expand. While this expansion of the radius of influence may come at the cost of longer remediation times, the time/cost tradeoff may be acceptable at some sites.

Section 3: Demonstration Design

3.1 Performance Objectives. The performance objectives are designed to establish under what circumstances passive bioventing can be practical and cost effective. The two primary performance objectives for this demonstration project were:

1. Achieve an adequate radius of influence to be economically viable; and,
2. Achieve airflow rates sufficient to meet the biological demand.

Because the radius of influence and oxygen demand of microorganisms will be site-specific, the success of the technology will be based on the ability to achieve an economical radius of influence from vent wells and induce airflow needed to meet site-specific oxygen demands. The treatment area and air flow requirements must be met economically, without an excessive number of vent wells compared to a conventional bioventing approach.

The stated numerical goals of the demonstration that indicate technical and economic success of passive bioventing included:

- peak air flow rates of a least 1 cubic foot per minute (cfm) per well, or
- total air flow rates of at least 1,200 cubic feet per day (cfd) per well, and
- a radius of influence of at least 10 feet per well.

3.2 Physical Setup and Operation. The initial phase of the demonstration was conducted in March 1998 and consisted of installing one vent well (PFFAVW02). The vent well was installed using hollow-stem augering techniques and was constructed of 4-inch inside diameter (ID) Schedule 40 polyvinyl chloride (PVC) casing and 0.04-inch slotted screens. The vent well was screened between 25 and 65 feet bgs, below the near surface silty sand and clay/silt layers (Figure 4).

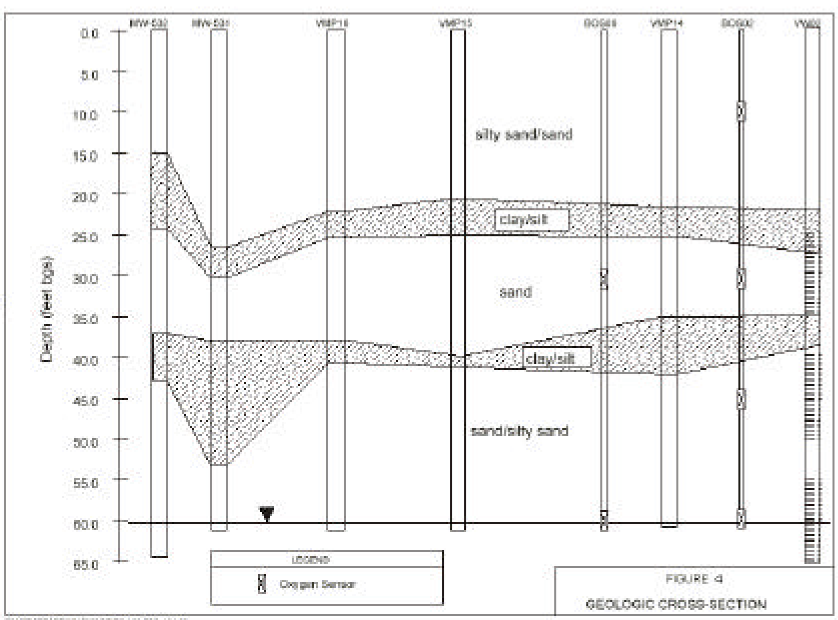


FIGURE 4
GEOLOGIC CROSS-SECTION

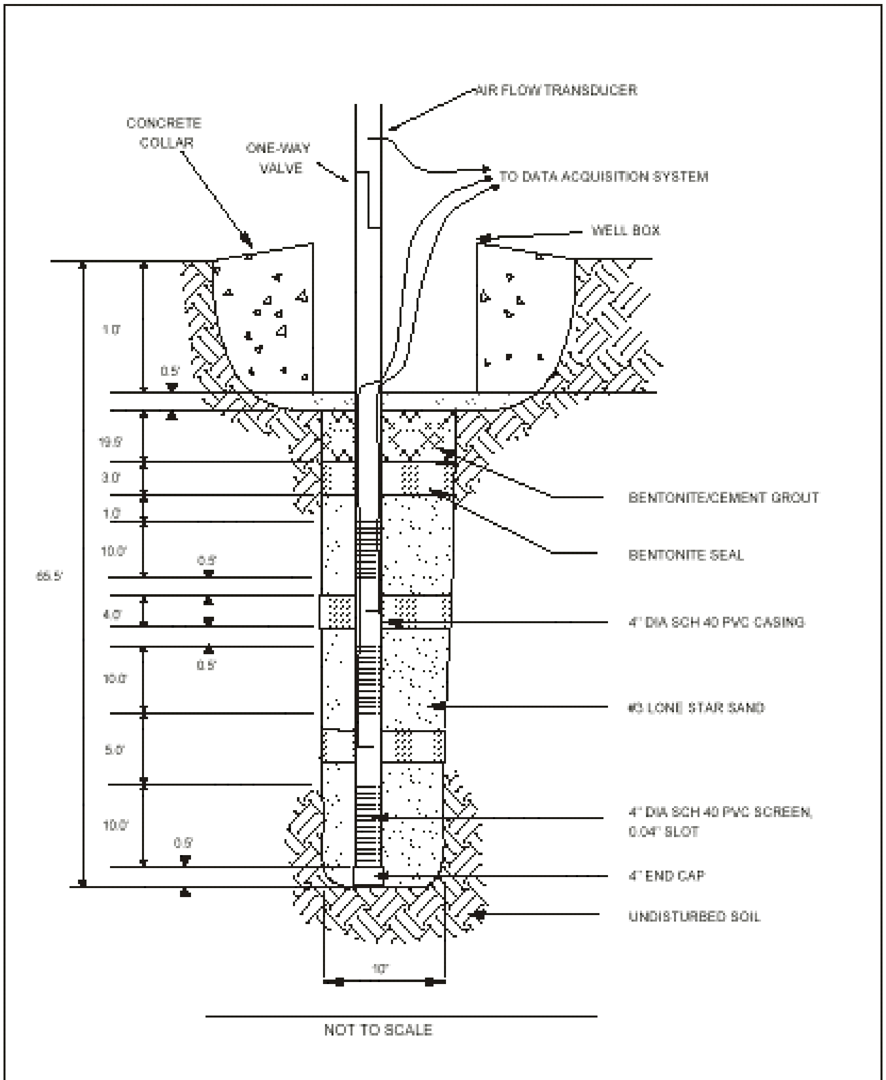
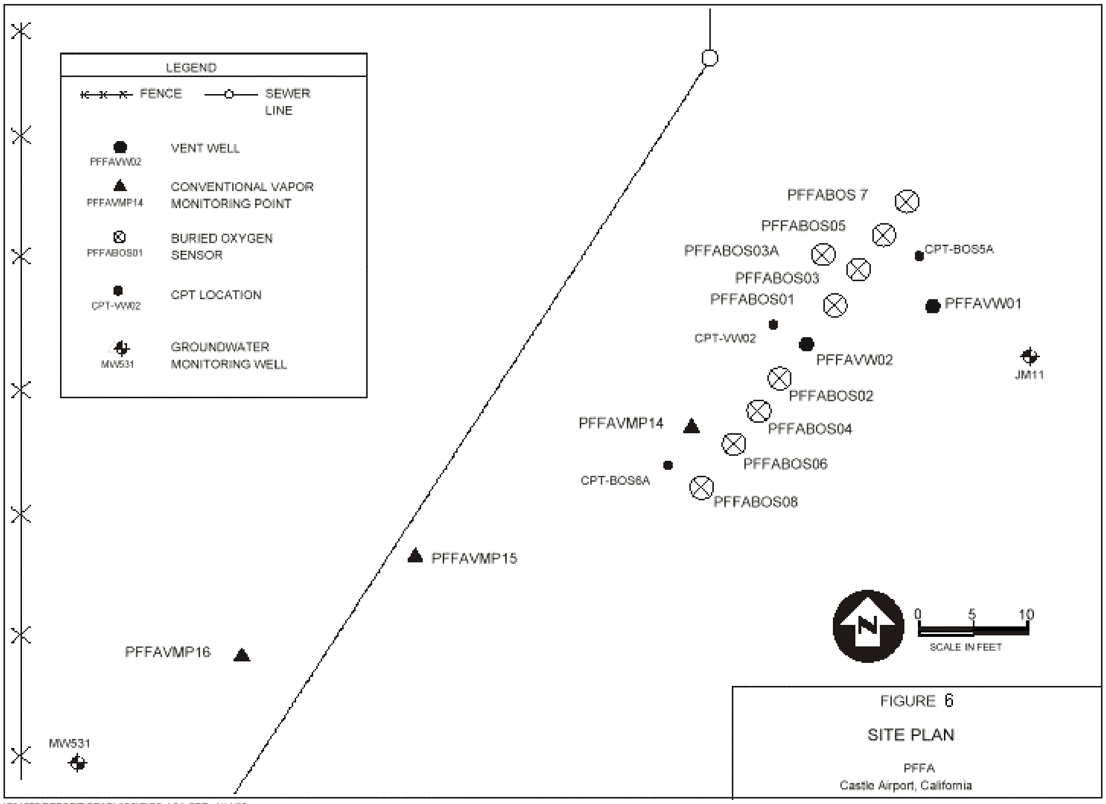


FIGURE 5
VENT WELL CONSTRUCTION AND AIR FLOW TRANSDUCER PLACEMENT
PFFA
Castle Airport, California

The vent well was constructed with three isolated 10-foot screened intervals 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. Figure 5 shows that the vent well was constructed with transducers used to measure air flow at the different screened intervals and the overall air flow.

3.3 Vapor Monitoring Points. A total of eight vapor monitoring points (VMPs) were installed along a straight line with the vent well between the 4th and 5th VMP. The four VMPs along each arm were installed at approximately 4, 8, 12, and 16 feet from PFFAVW02 (Figure 6).

Each of the VMPs is constructed using directly-buried oxygen sensors with an integrated sampling and pressure measurement port (Datawrite Research Corp. model XTM253SP) strapped to 2-inch ID solid PVC casing running the length of the borehole. Sensors at the four innermost VMPs (i.e., those located at 4 and 8 feet from the PFFAVW02) are installed at approximately 10, 30, 45, and 60 feet bgs. Screens at the remaining four VMPs (i.e., those located at 12 and 16 feet from the PFFAVW02) are installed at approximately 30 and 60 feet bgs. Each of the sensors is isolated at depth using bentonite seals between the sensors and sand filter packs. The sensor depths and their relationship to the lithologic zones at the site and the screened intervals of PFFAVW02 are shown on Figure 4. Typical construction details for the VMPs are provided on Figure 7.



3.4 Borehole Verticality Survey. After installation of the vent well and the VMPs, a borehole verticality survey was conducted by Norcal Geophysical (Petaluma, California) using a Robertson Geologging, Ltd. verticality probe. The primary purpose of the verticality survey was to ensure the vertical orientation of the borings and correct for any significant deflection or note any intrusion into the sand filter pack of the vent well. The verticality survey was considered important since the distance between the innermost VMPs and the vent well was four feet.

The results of the verticality survey showed deviations from vertical ranged between approximately 0.10 and 1.1 feet. The largest deviations (1.1 feet) occurred at PFFABOS02 and PFFABOS08, located at 4 and 16 feet from the vent well, respectively, at 59 feet bgs. While the maximum deviations at these locations were relatively significant compared to the horizontal distance to the nearby vent well (4 feet), the direction of the deviation was away from the vent well. The vertical deviation was not large enough to suspect that the VMP sensor or sample port had been installed in the vent well sand filter pack.

3.5 One-Way, Passive Valve Construction. A one-way, passive valve was constructed and used during testing to enhance the potential treatment radius. The valve was constructed of 4-inch ID, clear PVC by Nisei Plastics (Oakland, California). During the first two weeks of testing with the passive valve, single-celled foam rubber was used as the material for the internal flow control seal in the valve. However, test results indicated that some leaking was

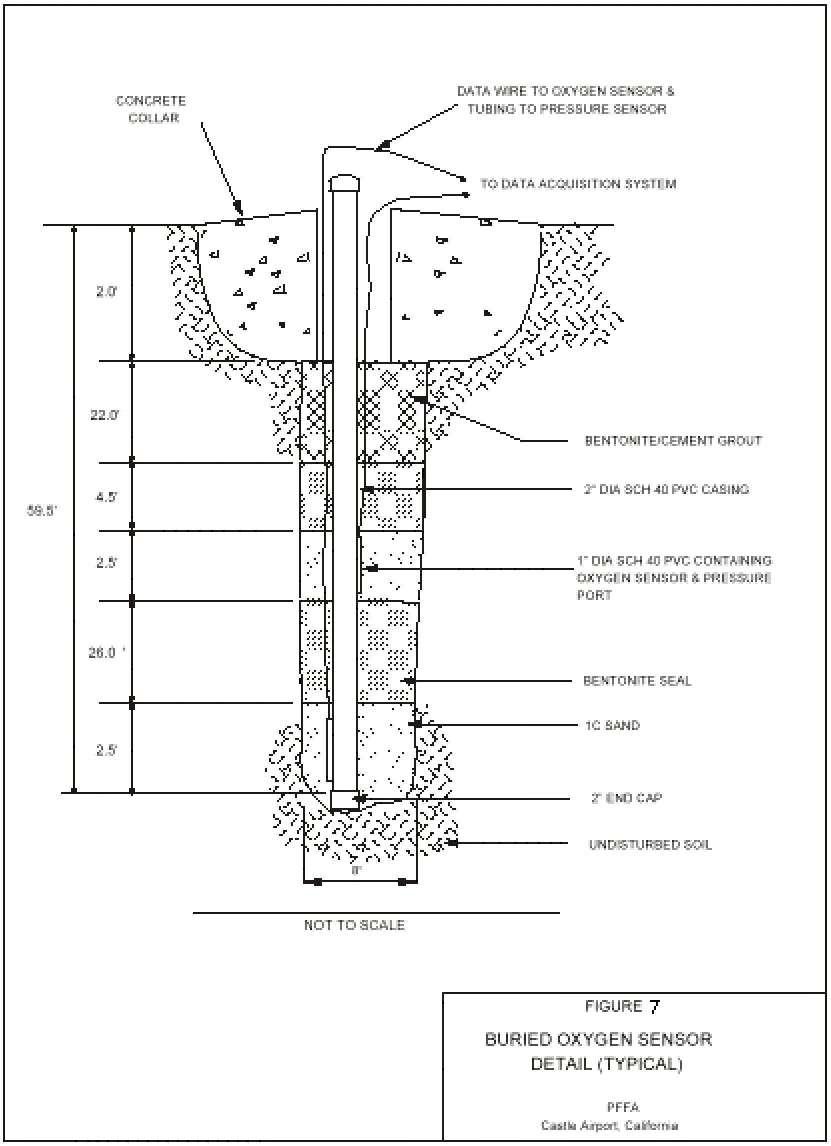


FIGURE 7
BURIED OXYGEN SENSOR DETAIL (TYPICAL)

occurring with this material. A passive valve using a mylar sheet was subsequently substituted and used for the remainder of the demonstration tests.

3.6 Testing and Operation. Following installation of the vent well, VMPs/directly-buried sensors, and the data acquisition system, the demonstration was conducted over a six-month period (starting in late April 1998 and continuing through late October 1998). A total of 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 additional respiration data and allow subsurface oxygen concentrations to reach equilibrium concentration prior to the initiation of Test 4. Test 4 evaluated the effect of the one-way, passive valve on the radius of influence.

Tests 5 and 6 were conducted based on an analysis of the data from Test 2, which indicated the occurrence of a significant weather-front related event (see discussion in Section IV) and, therefore, were not comparable to the other tests.

Table 1
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 (respiration testing and equilibrium resting period)	02 Jul - 15 Jul
TEST 4	Vent well open, with one-way, passive valve installed	16 Jul - 06 Sep
TEST 5	Vent well closed (equilibrium resting period in preparation for TEST 6)	06 Sep - 03 Oct
TEST 6	Vent well open, without one-way, passive valve; repeat of TEST 2	03 Oct - 30 Oct

3.7 Monitoring Procedures. The forces that cause subsurface airflow occur over a 24-hour period. The number of samples required to monitor the changes justifies the investment in dedicated sensors and use of data loggers. A data acquisition system was constructed and used to monitor:

- barometric pressure;
- air flow rates (total and between the three screened intervals in the vent well);
- subsurface differential pressure at each VMP screen;
- subsurface oxygen concentration at each VMP screen (directly-buried sensors);
- ambient air temperature; and,
- groundwater elevation.

The data acquisition system consisting of:

- Multiple data loggers (In-Situ, Inc. Hermit models 2000/3000) which included an integrated barometric pressure sensor.
- A K-type thermocouple (Cole-Parmer Digi-Sense Model 8528-40) used to measure atmospheric temperature.
- Bidirectional pressure transmitters (Dwyer model 607) used to measure subsurface differential pressure at each of the 24 integrated pressure measurements ports connected to the buried oxygen sensors.
- Three airflow transducers (TSI model 8475) were used to measure airflow into and out of the vent well at different depth intervals. One of the transducers was installed at the surface to measure total airflow; the remaining two were installed between the screened intervals in the vent well to allow calculation of airflow into each of the screened sections.

- Directly-buried oxygen sensors with an integrated sampling and pressure measurement port (Datawrite Research Corp. model XTM253SP) were strapped to 2-inch ID solid PVC casing running the length of the borehole (Figure 7).
- A downhole pressure transducer (Instrumentation Northwest Model PS9000) installed in monitoring well JM11 to measure changes in groundwater elevation.

Sensor information was collected every 10 minutes.

The passive bioventing demonstration conformed to the maximum extent practical with the most current version of the following guidance documents:

- *Principles and Practices of Bioventing*, USEPA Office of Research and Development (ORD), EPA/540/R-95/534, September 1995.

- *Test Plan and Technical Protocol for a Field Treatability Test for Bioventing*, U.S. Air Force Center for Environmental Excellence (AFCEE), May 1992.

- *Addendum One to Test Plan and Technical Protocol for a Field Treatability Test for Bioventing - Using Soil-Gas Surveys to Determine Bioventing Feasibility and Natural Attenuation Potential*, AFCEE, February 1994.

- *A General Evaluation of Bioventing for Removal Actions at Air Force/Department of Defense Installations Nationwide*, Air Force Center for Environmental Excellence (AFCEE), June 1996.

- *Final Technology Demonstration Plan (Revision 2), Natural Pressure-Driven Passive Bioventing*. Prepared for Environmental Security Technology Certification Program (ESTCP), NFESC October 1997.

Soil and soil vapor contaminant concentrations were measured following the sample collection and analysis techniques specified in the *Technology Demonstration Plan, Site-Specific Addendum, Natural Pressure-Driven Passive Bioventing* (NFESC, 1998). Details on the field meters, sensors, and calibration procedures are provided in the *Natural Pressure-Driven Passive Bioventing Demonstration Report* (NFESC, 1999).

3.8 Analytical Procedures. The analytical methods used for each measurement and associated method are summarized in Table 2.

Table 2
Analytical Procedures

Media	Analyte	Method
Soil Organic & Moisture Content	Total Petroleum Hydrocarbons	8015M/8015B
	Volatile Organic Compounds	8020A/8260
	Soil Moisture Content	ASTM 2216
Soil Inorganic & 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

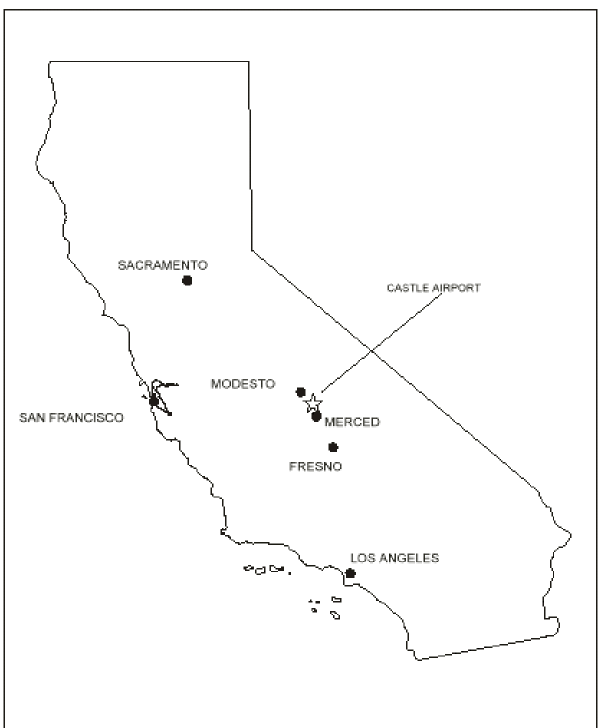
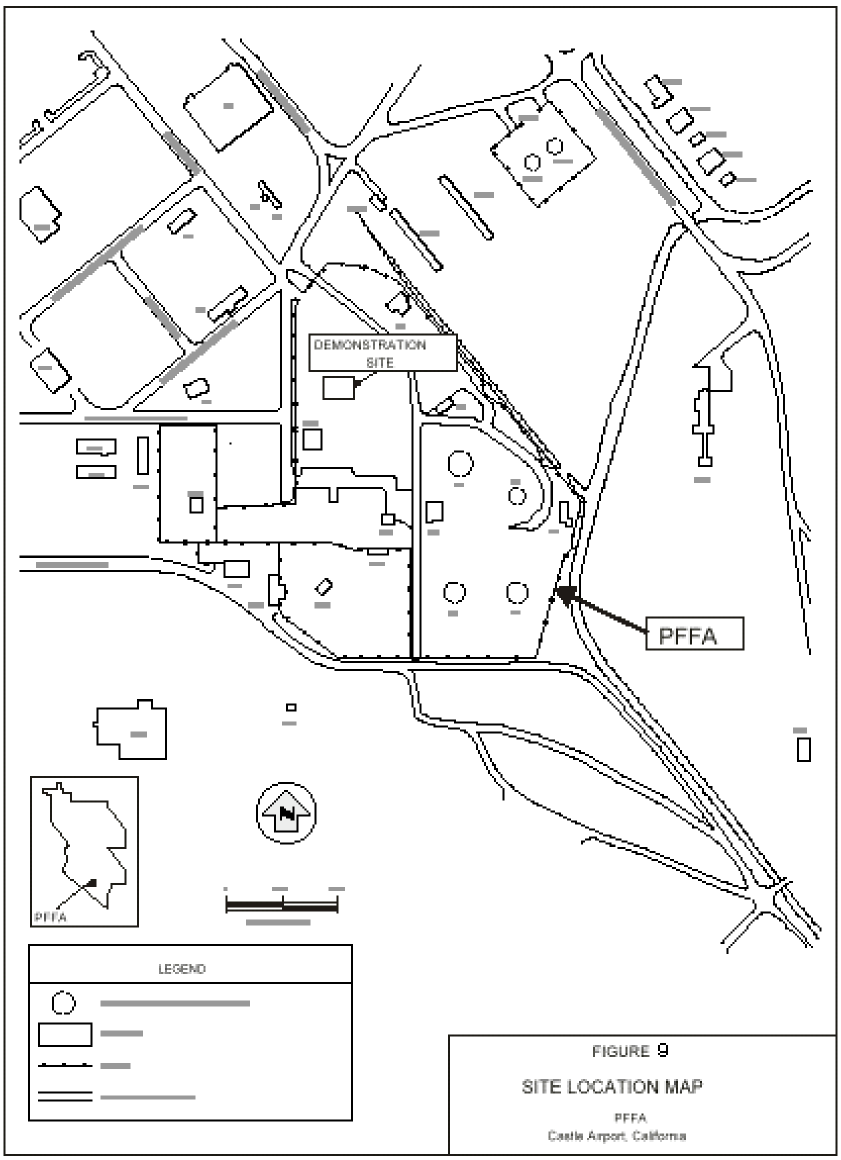


FIGURE 8
FACILITY LOCATION MAP
Castle Airport, California

3.9 Demonstration Site/Facility Background. Castle Airport (formerly Castle Air Force Base [AFB]) is located in Merced County, California, approximately 5 miles northwest of the city of Merced (Figure 8). It occupies approximately 3,000 acres of land and is comprised of runway and airfield operations, industrial areas, and several non-contiguous parcels of land located near the former base. Castle AFB was selected for closure under the Defense Base Closure and Realignment Act of 1990 and was officially closed in September of 1995. Environmental investigations, underground storage tank (UST) removals, and soil and groundwater cleanup operations are ongoing. Some parts of the former base have been leased to public and private entities.

The Petroleum, Oils, and Lubricants (POL) Fuel Farm Area (PFFA), built in the 1940's, is located in the southern portion of the Main Base Sector and was the bulk fuel storage and distribution facility (Figure 9). Approximately 18 USTs were formerly located and four above-ground storage tanks (ASTs) (3 million gallon total capacity) are currently located at the site. Extensive remedial investigations identified soil and groundwater contamination, primarily petroleum hydrocarbons, as a result of surface spills, leaking underground storage tanks, and fuel distribution lines. Most of the site is paved with asphalt or concrete or covered with gravel.

Based on the information available, the standard industrial classification (SIC) code most applicable to the site is 4581 (Transportation by Air — Airports, Flying Fields, and Airport Terminal Services) and the waste management practice that contributed to the site contamination is Petroleum, Oil, and Lubricant lines and underground storage tanks.



General selection criteria for passive bioventing sites were detailed in Section 3.1 of the Technology Demonstration Plan (TDP) (NFESC, 1997). A comparison of the criteria and the characteristics of the PFFA site at Castle Airport are summarized in Table 3. Detailed data are provided in the Technology Demonstration Plan, Site-Specific Addendum (NFESC, 1998).

Table 3
Selection Criteria

Criteria	PFFA Site Characteristic
Biodegradable contaminants	Contaminant concentrations in soil as high as 28,000 mg/kg TPH and 279 mg/kg BTEX
Soils are oxygen-deficient	Soil vapor oxygen concentrations were less than 1% in contaminated areas
Average diurnal barometric pressure changes greater than approx. 0.1 in. Hg	Diurnal barometric pressure changes measured at approx. 0.1 in Hg during short-term testing
Conventional bioventing is planned for the site (to provide leveraged data and facilitate cost comparison)	Conventional bioventing was selected for the PFFA in the feasibility study and is planned as a remedial action
For shallow groundwater sites, stratified soils with a relatively high horizontal air permeability relative to vertical air permeability	Groundwater is at approximately 60 feet bgs and soils at the site are highly stratified

3.10 Demonstration Site/Facility Characteristics.

3.10.1 Nature and Extent of Contamination. Remedial investigations have identified soil and groundwater contamination at the PFFA (NFESC, 1998; Jacobs, 1995). The soil is impacted with residual petroleum hydrocarbon contamination while the groundwater is contaminated with both petroleum hydrocarbons and chlorinated solvents. However, non-aqueous phase liquids (NAPLs) have not been found at the site. Soil and soil vapor sample analysis results indicate contamination is greatest in soils below 30 to 35 feet bgs and extends to groundwater.

The maximum detected concentrations of contaminants in soil are:

- 28,000 mg/kg total petroleum hydrocarbons as gasoline (TPH-g);
- 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 are:

- 54,000 part per million by volume (ppmv) TPH-g;
- 1,200 ppmv benzene, 820 ppmv toluene, 210 ppmv ethylbenzene, and 700 ppmv total xylenes.

The soil vapor is oxygen-depleted throughout the area, with the exception of some of the soil vapor from above 20 feet bgs. TVH readings are lower in the shallower soils.

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

3.10.2 Geology and Hydrogeology. The shallow subsurface stratigraphy at Castle Airport 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. Generally, the upper 20 feet of these deposits consist of eolian and Holocene flood plain sediments, while the deeper deposits consist of sequences of silts, sands, and gravels that increase in coarseness with depth. Hardpan composed of iron- and silica-cemented sands and silts is often encountered between approximately 2.5 and 15 feet below ground surface (bgs). Currently, shallow groundwater is generally encountered at approximately 50 to 70 feet bgs, although historically groundwater was as shallow as approximately 10 feet bgs in some areas. Groundwater pumping is extensive in the areas surrounding Castle Airport.

A plan view of the demonstration area is shown on Figure 6 and a generalized cross-section through the demonstration area is shown on Figure 4. The subsurface in the upper 20 feet is comprised predominantly of silty sand, overlying a laterally continuous silt layer between approximately 20 and 25 feet bgs. Between 30 and 35 feet bgs, sand with little to no fines predominates. This sand is underlain by another continuous clay/silt layer approximately 5 to 10 feet in thickness. Below this second clay/silt layer, sand extends to the groundwater table.

3.10.3 Soil Grain-Size Analysis. Selected soil samples collected from both previous investigations and the demonstration activities were submitted for grain-size analysis to compare against lithologic interpretations made in the field. Samples were collected from the upper silty sand between ground surface and approximately 20 feet bgs, the clay/silt layer between approximately 20 and 25 feet bgs, and the sand layers between approximately 25 and 35 feet bgs and below approximately 40 feet bgs. The results generally confirmed the lithologic interpretations made in the field, with significant silt and clay fractions measured in the clay/silt layer (greater than 90% clay/silt) and higher silt and clay fractions measured in the upper silty sand interval above 20 feet bgs (greater than 30% clay/silt) compared to the lower sand intervals (average of 16% clay/silt).

3.10.4 Soil Moisture and pH. Soil moisture and pH were measured for selected soil samples collected during the previous remedial investigations and during the installation of the wells for the demonstration. For vadose zone soil samples, soil moisture content ranged from 0.9 to 25.5 percent by weight (% by wt.), with average soil moisture content calculated at 5.8%. The moisture content for most samples was between 2% and 10%, a range considered optimal for bioventing since sufficient moisture is available for microorganisms but moisture content is not high enough to limit air permeability or air-filled porosity (USEPA ORD, 1995).

Soil pH values were measured between 7.30 and 8.13, within the range considered optimal for microbial activity.

3.10.5 Soil Nutrients. Nutrients required for microbial activity in subsurface environments include nitrogen, phosphorus, and iron. Selected soil samples collected during the installation of the vent well and VMPs at the demonstration site were analyzed for total Kjeldahl nitrogen (TKN), total phosphorus, and total and soluble iron.

Nutrient concentrations ranged from 32 mg/kg to 69 mg/kg TKN, 148 mg/kg to 238 mg/kg total phosphorus, 5,690 mg/kg to 10,000 mg/kg total iron, and 694 ug/L to 3,040 ug/L soluble iron. The concentrations of these nutrients are within the ranges considered sufficient for microbial activity (USEPA ORD, 1995) and indicate that available nutrients should not be limiting to microbial activity. Background concentrations of oxygen indicate that naturally occurring iron in the soils do not create a significant oxygen demand.

3.10.6 Alkalinity. Soil alkalinity, along with soil pH, is a standard measurement conducted at bioventing sites because alkalinity and pH can affect the evolution of carbon dioxide produced during microbial activity. Alkalinity and pH affect soil vapor carbon dioxide concentrations such that, in high alkalinity soils, carbon dioxide production appears to be low due to the formation of carbonates. Conversely in low alkalinity soils, carbon dioxide production correlates well with oxygen consumption.

Soil alkalinity was measured primarily for comparison of alkalinity at the Castle Airport to data from other bioventing test sites. Soil alkalinity at Castle Airport was less than 200 mg/kg (the laboratory reporting limit), although for some samples estimates were provided of between 15 mg/kg and 59 mg/kg. These results are consistent with the relatively high carbon dioxide concentrations measured in soil vapor at the site and are at the low end of concentrations measured at other bioventing test sites (USEPA ORD, 1995).

3.10.7 Oxidation Reduction Potential and Microbially Reducible Iron. Oxidation Reduction Potential (ORP) and microbially reducible iron were also 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 ranged from 164 mV to 206 mV and reducible iron ranged from less than 2.0 mg/kg (the laboratory detection limit) to 44 mg/kg.

Reducible iron concentrations were higher in the samples collected from 45 feet bgs, where soil contaminant concentrations were also highest, possibly indicating that some oxygen demand at these locations would occur due to the potential for reduced iron. However, the reducible iron concentrations were significantly less than the contaminant concentrations at those locations and, based on stoichiometry, would result in an oxygen demand far less than that required for microbial breakdown of the contaminants. Based on the ORP and reducible iron concentration data, the soils do not appear to be highly reducing nor are they expected to produce oxygen demands in excess of those predicted from respiration test data.

3.10.8 Air Permeability Testing. Air permeability testing was also conducted in the demonstration area during conventional bioventing pilot test activities in December 1997, prior to demonstration activities (Parsons ES, 1998). Two tests were conducted. The first test consisted of injecting air at PFFAVW01 in the shallow, finer-grained materials above 20 feet bgs. The second test consisted of injecting air in MW531 into the deeper, coarser-grained materials below 25 feet bgs. Results from the air permeability tests showed a smaller radius of influence (70 feet) and lower air permeability (3.9 darcies) could be expected in the shallow soils compared to the deeper soils (110 feet and 38 to 200 darcies). These results are consistent with the stratified geology of the site and shown on Figure 6. The air permeabilities in both lithologic zones are within the range considered suitable for bioventing (USEPA ORD, 1995).

3.10.9 *In Situ* Respiration Testing. Short-term, initial *in situ* respiration (ISR) tests were also conducted in the demonstration area during conventional bioventing pilot test activities in February 1998, prior to demonstration activities (Parsons ES, 1998). The ISR tests were conducted at PFFAVMP14, PFFAVMP15, and PFFAVMP16. Testing was conducted at two discrete depth screens at PFFAVMP14 (35 feet and 51 feet bgs), one discrete depth screen at PFFAVMP15 (42 feet bgs), and one discrete depth screen at PFFAVMP16 (35 feet bgs). The purpose of using multi-depth monitoring points was to verify that soil bacteria and oxygen demand were present within the entire vadose zone.

Results from the initial ISR tests indicate there were active microorganism populations within the oxygen-depleted zones that were tested. Initial oxygen-utilization rates measured at the demonstration area were low to moderate, ranging from 0.087% oxygen per hour (% O_2/hr) (2.1 %O_2/day) at PFFAVMP15 at 42 feet bgs to 0.29% O_2/hr (7.0% O_2/day) at PFFAVMP14 at 35 feet bgs, with a mean rate at all tested locations of 0.18% O_2/hr (4.2% O_2/day).

3.10.10 Climate. The climate of the Merced Area in central California, where Castle Airport is located, is semiarid, Mediterranean type and characterized by wet winters and long, dry summers with high temperatures often exceeding 100 degrees Fahrenheit (°F). Winters are very cool with high humidity. 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 rapid radiation, leading to large differences between day and night temperatures (frequently 40°F or more).

The mean annual precipitation is 12 inches. Approximately 85 percent of the precipitation falls between November and April. The average monthly relative humidity ranges from a high of approximately 75 percent during January to a low of approximately 30 percent in July.

Winds from the northwest prevail throughout most the year. Although the strongest winds occur between January and March, daily peak wind speeds are typically between 10 and 20 knots throughout most of the year. Winter precipitation events are usually preceded by winds from the southeast.

3.10.11 Barometric Pressure, Air Flow, and Differential Pressure. During the installation of the vent well and VMPs for the conventional bioventing pilot test, the field geologist noted that the site VMPs and monitoring wells were exhaling and inhaling air at various times during the day. In addition, during the air permeability testing, the field scientist noted that changes in barometric pressure were clearly affecting the pressure measurements used to infer radius of influence and calculate air permeability. The barometric pressure interference was so significant (resulting in subsurface differential pressure fluctuations in the VMPs on the order of 0.3 to 0.6 inches of water) that subsurface differential pressure in a background well needed to be measured periodically to correct for the interference.

Based on these observations, a short test was conducted to evaluate the effect of barometric pressure on subsurface differential pressure and airflow at the site. Details are provided in the Technology Demonstration Plan, Site-Specific Addendum (NFESC, 1998). Airflow as high as 11 cfm and differential pressures as high as 0.9 inches H_2O were observed. Barometric pressure had a clear effect on both air flow and differential pressure, with air flowing into the well during periods of increasing air pressure and air flowing out of the well during periods of decreasing air pressure. Both long-term weather front changes and short-term diurnal changes affected both airflow and subsurface differential pressure.

Based on these results, more extensive testing to determine the radius of oxygen influence due to barometrically-induced air flow was of interest and the PFFA was selected as the passive bioventing demonstration site.

Changes in soil vapor oxygen concentration with time and distance from the vent well were used to determine the radius of influence of the system. To facilitate this evaluation, oxygen concentrations were measured at VMPs located in two directions and several distances from the vent well. These measurements were collected in both the VMPs containing directly-buried oxygen sensors (PFFABOS01 through PFFABOS08), as well as the conventional bioventing VMPs (PFFAVMP14, PFFAVMP15, and PFFAVMP16) previously installed at the demonstration site.

4.1 Test 1. Test 1 was designed to evaluate the effects of barometric pressure fluctuations on subsurface oxygen and pressure conditions without any system enhancement. Figure 10 shows subsurface differential pressure response for 2 depths, 10 feet bgs and 30 feet bgs. As expected, the differential pressure is negative at both depths during periods of increasing barometric pressure and positive during periods of decreasing barometric pressure. The magnitude of the subsurface differential pressure is significantly greater at 30 feet bgs compared to 10 feet bgs. However, the magnitude of the response at 30 feet bgs was essentially identical to that at 45 feet and 60 feet bgs in all VMPs. This observation supports the conclusion that the overlying lower permeability silty sand which extents from ground surface to approximately 20 feet bgs and the clay/silt layer between approximately 20 and 25 feet bgs is preventing the equalization of subsurface and atmospheric pressure.

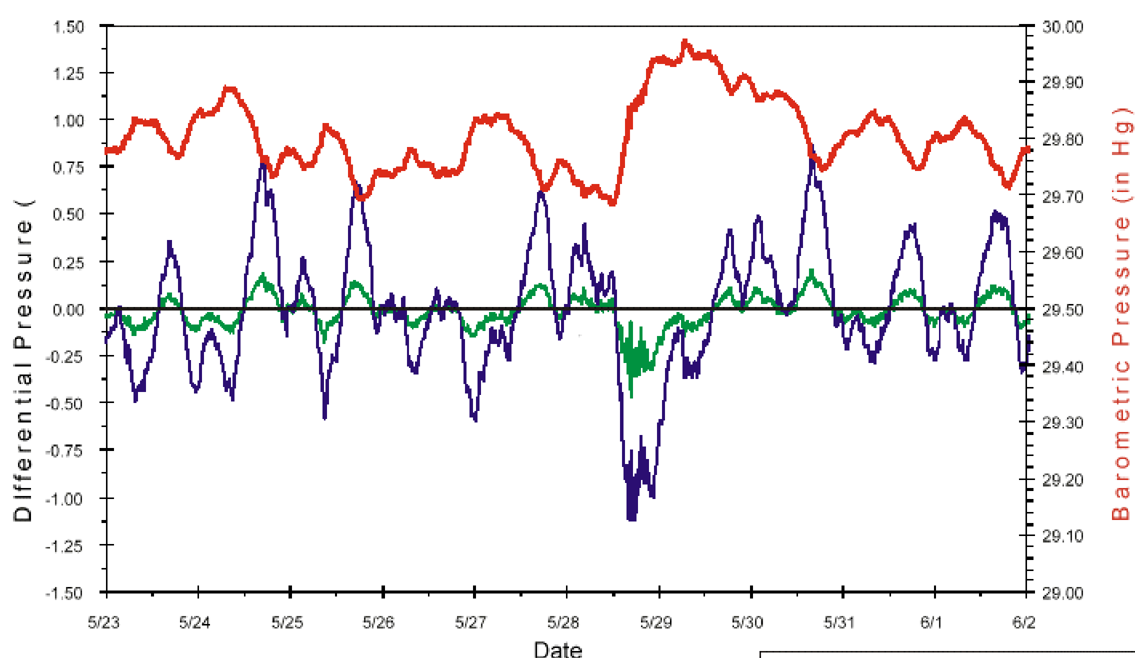


FIGURE 10

SUBSURFACE PRESSURE RESPONSE DURING TEST 1

PFFA
Castle Airport, California

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4.2 Test 2. Test 2 was designed to establish natural rates of airflow into and out of the vent well and the radius of influence from this cyclical air movement without the use of the passive valve. A relatively significant weather front-related barometric pressure change occurred during the first three days of the test (6/15-6/18 as shown in Figure 11), followed by primarily diurnal barometric pressure changes. Both the weather-front and diurnal barometric pressure changes resulted in significant airflow rates both into and out of the vent well. Airflow rates as high as 20 cfm occurred during the weather front changes and as high as 12 cfm occurred during diurnal changes. These air flow rates are comparable to typical airflow rates used during conventional bioventing (USEPA ORD, 1995) and demonstrate the feasibility of using a passive bioventing approach at this site.

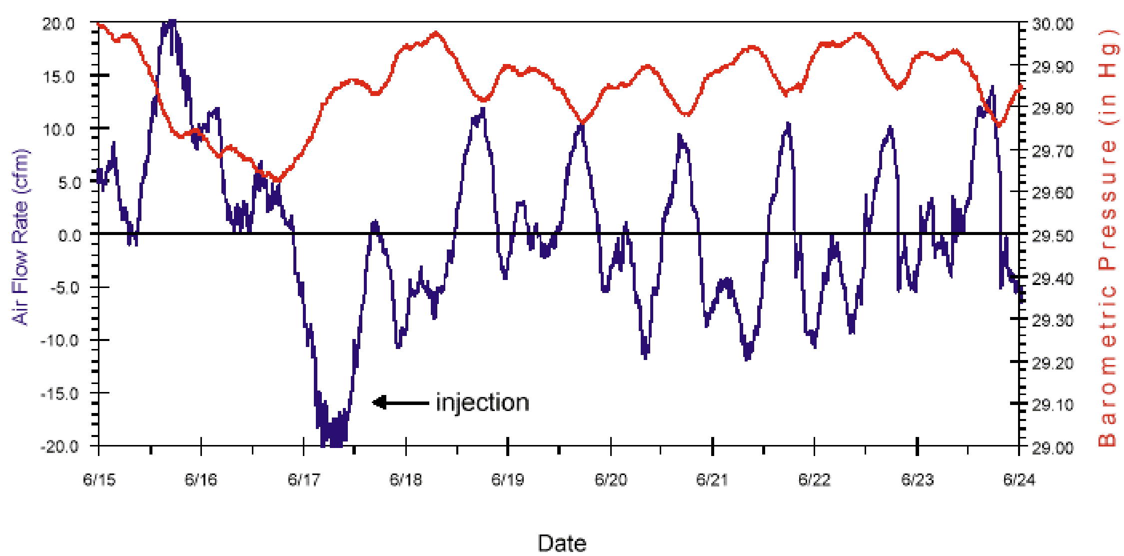

FIGURE 11

AIR FLOW vs. BAROMETRIC PRESSURE DURING TEST 2

PFFA
Castle Airport, California

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Airflow was approximately equal between the upper-screened interval and the middle-screened interval. Air flow into the lower screened interval was generally much lower compared to flow into the two upper intervals (generally less than 5% of the total flow and never exceeding 18% of the total flow). This is likely a result of the shorter length of exposed screen (only 5 feet was exposed above groundwater) and because the screen was probably within the capillary fringe.

Oxygen concentrations increased rapidly from near zero and were sustained at greater than 12% at the VMPs located within 8 feet of the vent well and greater than 6% at the VMPs located within 16 feet of the vent well. Oxygen concentrations remained low in the VMP screens which were installed at 10 feet bgs and located within the upper silty sand, indicating that the clay/silt layer at 20 to 25 feet was acting, as expected, as a confining layer to vertical air flow (the vent well was not screened within the upper silty sand).

While these results indicated that airflow rates could significantly increase oxygen concentrations, the radius of influence was determined to be 16 feet. In addition, the significant airflow which occurred during the weather-front related barometric pressure changes appeared to have been responsible for the significant initial increases in oxygen concentration which prevented an evaluation of oxygen response solely due to diurnal barometric pressure response.

4.3 Test 3. Test 3 was designed to collect additional respiration data and allow subsurface oxygen concentrations to reach equilibrium concentration prior to the initiation of Test 4. Oxygen concentrations decreased to near zero with two weeks at most locations and depths. Field measurements were also conducted to confirm readings from the buried oxygen sensors prior to the start of Test 4.

The rate of decline in oxygen concentrations resulted in calculated oxygen utilization rates between 0.48% O_2/day and 1.5% O_2/day (average rate of 1.0% O_2/day), somewhat lower than the rates measured during the previous short-term *in-situ* respiration (ISR) tests. It is common for such “area” respiration tests as conducted during Test 2, where a significant volume of soil is aerated, to show lower respiration rates than “point” respiration tests, as conducted during the previous ISR testing.

4.4 Test 4. Test 4 was the primary test for the passive bioventing demonstration and was used to evaluated the effect of the passive valve on the radius of influence.

Figure 12 shows that the daily airflow rates ranged from a minimum of 27 cfd to a maximum of 9,300 cfd, with an average daily airflow rate of 3,400 cfd. It should be noted that the minimum daily air flow rate of 27 cfd was the only daily air flow rate less than 300 cfd throughout the entire seven week test period. Peak daily airflow rates ranged from 5.1 cfm to 15 cfm, although airflow rates near the daily peak airflow rate were rarely sustained for more than 30 minutes to an hour.

The Test 4 results show that the one-way passive valve could significantly increase and sustain oxygen concentrations at significant distances from the vent well (Figure 13). Test 4 was continued for seven weeks to determine the long-term radius of influence when using the passive valve. Oxygen measurements were then taken at PFFAVMP15, located at 41.5 feet from the vent well (Figure 6), following seven weeks of air injection using the passive valve.

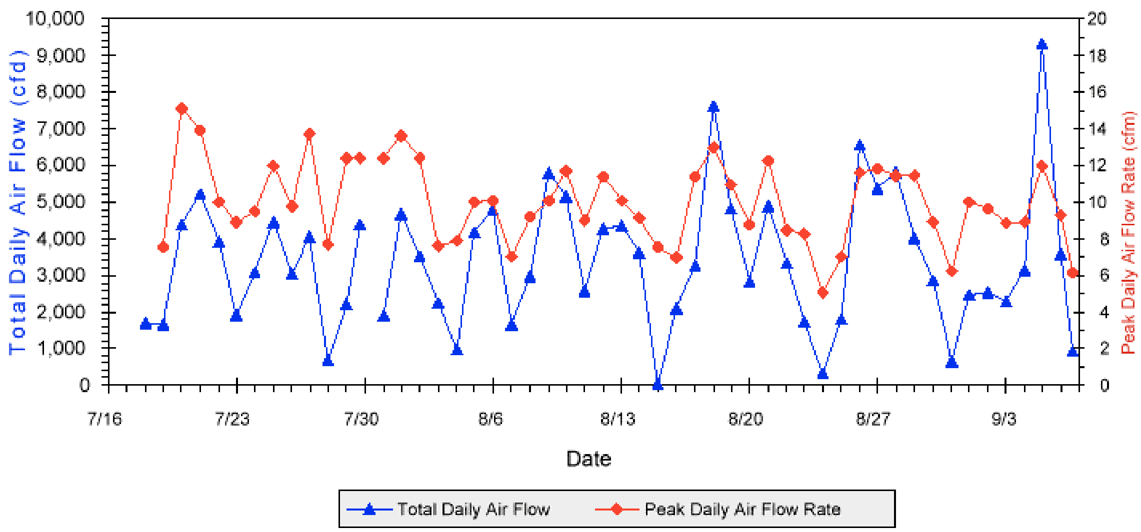
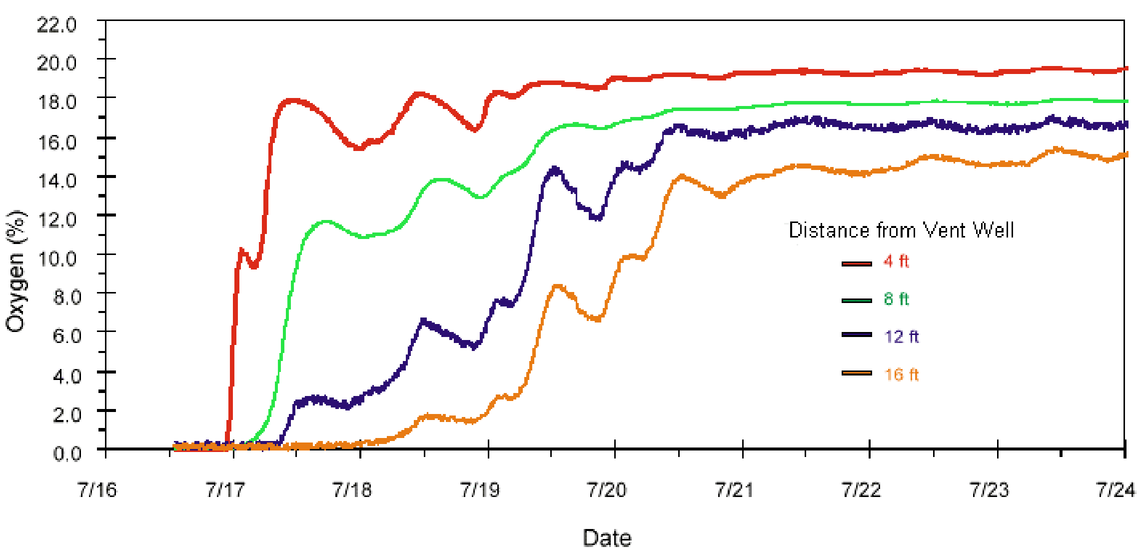


FIGURE 12

DAILY AIR FLOW RATES
DURING TEST 4

PFFA
Castle Airport, California



Test 4 conducted with one-way passive valve

FIGURE 13

OXYGEN RESPONSE
DURING TEST 4

PFFA
Castle Airport, California

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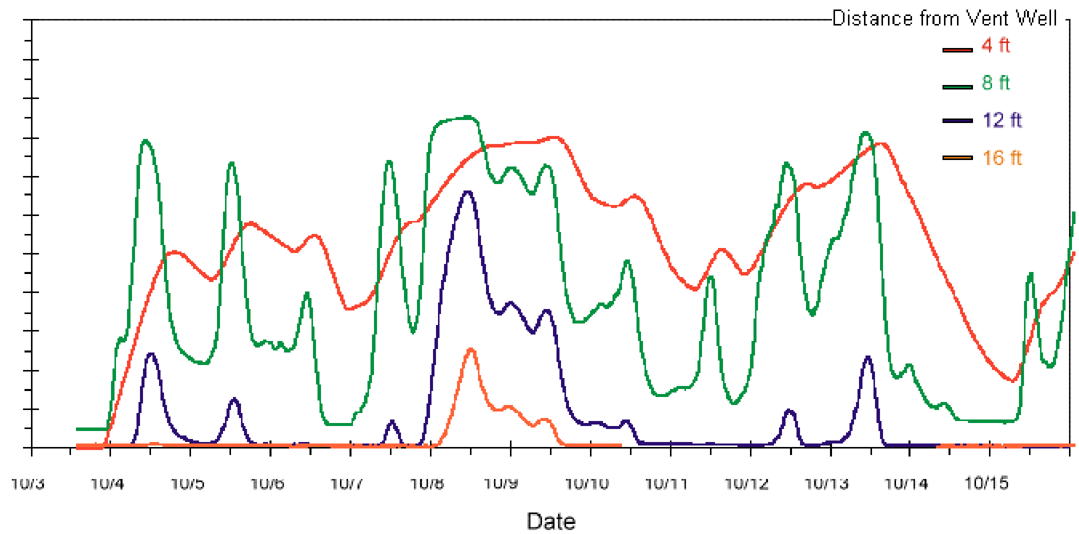
Oxygen concentrations in PFFAVMP15 at 42 feet bgs increased from 0% at the start of Test 4 to 5.5% at the end of Test 4. Since 5% is typically the oxygen concentration used to indicate that microbial activity is not being oxygen limited, this result provides some evidence that the passive bioventing radius of influence is approximately 42 feet.

4.5 Tests 5 and 6. At the end of Test 4, an analysis of the data from Test 2 indicated that a repeat of the configuration used in Test 2 was needed due to weather-related barometric pressure changes. Therefore, Tests 5 and 6 were conducted, which were essentially a repeat of the same conditions of Test 1/Test 3 (vent well remained closed) and Test 2 (vent well was open without the passive valve installed). As during Test 3, oxygen concentrations decreased to 0% within a few weeks. Respiration rates ranged from 0.38% O_2/day to 0.88% O_2/day during Test 5. These respiration rates were somewhat lower that from Test 3, but more consistent from location to location. This probably indicates that some reductions in the most biodegradable contaminants occurred during the extended period of air injection during Test 4.

The oxygen response for Test 6 (Figure 14) is comparable to the conditions which occurred in Test 4 that were the result of regular diurnal changes rather than weather-front related events.



Test 6 conducted without the one-way passive valve

FIGURE 14

OXYGEN RESPONSE
DURING TEST 6

PFFA
Castle Airport, California

\731272\REPORT\GRAPHICS\FIGS_L8B.CDR 1/11/99

Significant fluctuations in oxygen concentration also occur at all locations as the net influx of air is substantially lower without the passive valve. The fluctuations are caused by respiration as well as the reversal of airflow, which occurs during decreasing barometric pressure. The air flow reversal causes previously injected air to move back toward the vent well and brings in oxygen-depleted air from outside the treatment area. When compared to the oxygen response with the passive valve installed during Test 4 (Figure 4), this result clearly indicates the benefit of the passive valve in increasing the radius of influence.

4.6 Performance Objectives. The results from Test 4 which utilized the one-way passive valve show that the air supply during passive bioventing was sufficient to meet biologic demand and in fact consistently exceeded the numerical goals of 1 cfm and 1,200 cfd. The radius of influence for Test 4 was greater than the goal of 10 feet, on the order of 42 feet after seven weeks.

A conventional bioventing pilot test previously conducted at the demonstration site indicated that a radius of influence of 110 feet could be expected in the deeper vadose zone soils (those below 25 feet bgs).

As expected, the passive bioventing radius of influence is significantly smaller than the conventional bioventing radius of influence. However, it is expected that the radius of influence from a passive bioventing system would approach that of a conventional bioventing system over a relatively long time period (on the order of several months, much longer than the period of testing during this demonstration). Although initially the radius of influence will be limited by the microbial demand near the vent well, as areas near the vent well are remediated and the oxygen demand is satisfied, the radius of influence would expand (i.e., the oxygen-utilization rate would decrease).

For example, if the oxygen-utilization rate dropped from 1.0% O_2/day to 0.25% O_2/day, the predicted radius of influence would be 85 feet, based on expected declining oxygen-utilization rates over time (NFESC, 1999). This compares favorably with the conventional bioventing radius of influence of 110 feet which is primarily limited by induced pressure differences from the blower and vertical air flow components rather than oxygen-utilization rate. A passive bioventing vent well design which relied upon this long term radius of influence based on decreasing oxygen-utilization rates would not require a significantly greater number of wells than a conventional bioventing system (approximately 1.5 times as many vent wells for the same area of coverage). Results from the AFCEE Bioventing Pilot Test Initiative indicate that decreases in oxygen-utilization rates of this order of magnitude could be expected within 6 months to a year of bioventing. While the expansion of the radius of influence may come at the cost of longer remediation times, the time/cost tradeoff may be acceptable at some sites.

Section 5: Cost Assessment

The information included in this section provides an assessment of the expected operational costs for passive bioventing when implemented, not the demonstration costs. For comparison purposes, the expected costs are given for a single site of approximately the same size as the Castle Airport demonstration area, approximately 115,000 square feet (ft^2) or 2.6 acres.

Using the second level work breakdown structure (WBS) coding system detailed in the *Guide to Documenting Cost and Performance for Remediation Projects* (USEPA, 1995), costs for a typical passive and conventional bioventing system for a site of similar size to the demonstration area were estimated. These costs are shown in Table 4.

Table 4
Cost Comparison, Passive Bioventing vs. Conventional Bioventing

				Passive Bioventing		Conventional Bioventing		
WBS	**Description**	Unit Cost ($)	Units	Units	Cost ($)	Units	Cost ($)	Cost Basis
Before Treatment Cost Elements								
33-01	Mobilization and Preparatory Work							
	Design Costs	28,400	each	1	28,400	1	28,400	NFESC, 1996
	Health and Safety Plan	10,000	each	1	10,000	1	10,000	NFESC, 1996
	Pilot-Scale Work Plan	10,000	each	1	10,000	1	10,000	NFESC, 1996
	Full-Scale Remedial Action Work Plan	25,000	each	1	25,000	1	25,000	NFESC, 1996
	Quality Assurance Plan	10,000	each	1	10,000	1	10,000	NFESC, 1996
	Subtotal				**83,400**		**83,400**	
33-02	Monitoring, Sampling, Testing, and Analysis							
	Fixed Sampling and Testing Equipment	7,870	each	1	7,870	1	7,870	NFESC, 1996
	Soil Gas Survey	8,635	each	1	8,635	1	8,635	Greg Drilling
	Pilot Testing (incl. drilling but not analytical costs)	25,949	each	1	25,949	1	25,949	NFESC, 1996
	Soil Analysis (during pilot & full-scale install)	104	sample	35	3,649	35	3,649	NFESC, 1996
	Soil Vapor Analysis (during pilot & full-scale install)	130	sample	14	1,820	14	1,820	NFESC, 1996
	Subtotal				**47,923**		**47,923**	
33-03	Site Work							
	Trenching	16	foot	0	-	850	13,600	Marcor
	Electrical Utilities	3,000	total	0	-	1	3,000	Atwater Electric
	Subtotal				**-**		**16,600**	
Treatment Cost Elements								
33-11	Biological Treatment							
	Operations & Maintenance (passive)	1,998	yr	4	7,992	0	-	NFESC, 1996
	Operations & Maintenance (conventional)	11,113	yr	0	-	3	33,339	NFESC, 1996
	Follow-up Respiration Testing	4,569	yr	2	9,138	2	9,138	NFESC, 1996
	Passive Valves	149	each	6	894	0	-	Nisci/Ryan Herco
	Field Instrument Rental	1,760	total	1	1,760	1	1,760	Hazco
	Blower System	4,162	each	0	-	1	4,162	NFESC, 1996
	VW Installation (full-scale, but not pilot test)	5,946	each	5	29,730	2	11,892	NFESC, 1996
	VMP Installation (full-scale, but not pilot test)	5,720	each	2	11,440	2	11,440	NFESC, 1996
	Subtotal				**60,954**		**71,731**	
After Treatment Cost Elements								
33-21	Demobilization							
	Well Abandonment	17	foot	715	12,155	520	8,840	Greg Drilling
	Closure Soil Sampling	75	Sample	18	1,350	18	1,350	NFESC, 1996
	Closure Soil Vapor Sampling	130	Sample	9	1,170	9	1,170	NFESC, 1996
	Final Report	50,000	each	1	50,000	1	50,000	NFESC, 1996
	Subtotal				**64,675**		**61,360**	
33-9X	Other Costs							
	Contingency	26,200	each	1	26,200	1	26,200	NFESC, 1996
	Subtotal				26,200		26,200	
TOTAL COST					**28,152**		**307,214**	
COST PER CUBIC YARD TREATED					**1.93**		**2.09**	

Costs were estimated using the *Bioventing Cost Estimator (BVCE) and User's Guide* (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 the PFFA at Castle Airport. The costs include the following activities:

- Data review
- Site visits/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 are included in Table 4 for both a conventional bioventing system and a passive bioventing system for the same site. The *Bioventing Cost Estimator* calculated that the remediation area would require 3 vent wells, 5 VMPs (3 for the pilot test and 2 additional VMPs for the full-scale system), and one, 150 cfm blower system. An upgrade to the existing electrical system (e.g., new distribution panels and meters) was required for the blower system; however, electrical power itself was already at the site. Trenching and asphalt surface repair blower manifold system which distributes are to the vent wells would also be required for the conventional system design.

The passive bioventing system did not require a blower, electrical system upgrade, or trenching and surface repair; however, one-way passive valves were required. Based on an 85 feet radius of influence, the *Bioventing Cost Estimator* calculated that the remediation area would require require 6 vent wells. It was assumed that the number of VMPs would remain the same for both systems since the area treated was the same size.

The time period from initial installation to closure sampling was estimated at 3 years for the conventional system based on experience gained during the AFCEE Bioventing Initiative. The time period for remediation for the passive system was estimated at 4 years due to the lower air flow rates. Included in the operation and maintenance (O&M) costs were yearly *in-situ* respiration tests. It was assumed that all other costs (e.g., work plans, administration, regulatory oversight) remained the same for both systems.

As shown on Table 4, a passive bioventing system for this site is very cost-competitive with the conventional bioventing system. The total cost (approximately $283,000) and unit cost (approximately $1.90 per cubic yard) are somewhat lower for the passive system even though it required twice as many vent wells to cover the same area. This estimate shows that with an adequate radius of influence, the cost to install more vent wells with a passive system can be more than offset by the costs to install a blower, electrical power, and trenching and piping and to operate and maintain a conventional bioventing blower system. The yearly power costs alone for the blower are approximately $5,000, while the cost to install the trenching and piping at such a large, asphalted site with many subsurface utilities was approximately $14,000. These savings along with other yearly O&M savings more than make up for the costs to install additional vent wells and operate the system for a longer period of time.

Figure 15 shows the discounted cash flow based on the above assumptions. The cash flow summary was generated using the P2/FINANCE,Version 3.0, (Tellus Institute, 1996) software.

Alt1 vs. Base | Alt2 vs. Base | Calc | Help | Print . . .

INCREMENTAL CASH FLOW ANALYSIS

Alternative Scenario 1 vs. Base Scenario

Analysis Name: Natural Pressure-Driven Passive Bioventing | 5/1/99 | Cash Flow-Alt1 v. Base-pg.1

Operating Year	0	1	2	3	4	5	6	7
INCREMENTAL INITIAL INVESTMENT COSTS								
Project Design	0	0	0	0	0	0	0	0
Full Scale Installation	0	(16,256)	0	0	0	0	0	0
Pilot Test	0	0	0	0	0	0	0	0
Closure	0	0	0	0	(70,412)	76,814	0	0
Contingency	0	0	0	0	0	0	0	0
Depreciated costs	(4,162)	0	0	0	0	0	0	0
none	0	0	0	0	0	0	0	0
none	0	0	0	0	0	0	0	0
none	0	0	0	0	0	0	0	0
none	0	0	0	0	0	0	0	0
Other	0	0	0	0	0	0	0	0
Other	0	0	0	0	0	0	0	0
Other	0	0	0	0	0	0	0	0
Other	0	0	0	0	0	0	0	0
Total Initial Investment Costs	(4,162)	(16,256)	0	0	(70,412)	76,814	0	0
INCREMENTAL ANNUAL OPERATING (COSTS)/SAVINGS								
Operation and Maintenance		9,434	9,764	10,106	10,460	(2,373)	0	0
Utilities		0	0	0	0	0	0	0
Direct Labor (Wage/Salary, Benefits)		0	0	0	0	0	0	0
Waste Management (Labor, Materials)		0	0	0	0	0	0	0
Regulatory Compliance (Labor, Materials) #1		0	0	0	0	0	0	0
Regulatory Compliance (Labor, Materials) #2		0	0	0	0	0	0	0
Product Quality (Labor, Materials)		0	0	0	0	0	0	0
Revenues - Product		0	0	0	0	0	0	0
Revenues - By-product		0	0	0	0	0	0	0
Insurance		0	0	0	0	0	0	0
Future Liability		0	0	0	0	0	0	0
Other		0	0	0	0	0	0	0
Other		0	0	0	0	0	0	0
Other		0	0	0	0	0	0	0
Total Annual Operating (Costs)/Savings		9,434	9,764	10,106	10,460	(2,373)	0	0
INCREMENTAL TAX CALCULATION								
Annual Operating (Costs)/Savings		9,434	9,764	10,106	10,460	(2,373)	0	0
- Depreciation		(1,434)	(1,994)	(745)	155	453	0	0
- Expensed Initial Investment Costs		0	(16,256)	0	0	(70,412)	76,814	0
+ Taxable Gain (Loss) on Salvaged Equipment		0	0	0	(4,234)	1,469	0	0
Taxable Income		10,868	28,014	10,851	6,071	69,054	(76,814)	0
Income Tax at 41.9%		4,551	11,730	4,544	2,542	28,915	(32,164)	0
INCREMENTAL CASH FLOW CALCULATION								
Annual Operating (Costs)/Savings		9,434	9,764	10,106	10,460	(2,373)	0	0
- Income Tax		4,551	11,730	4,544	2,542	28,915	(32,164)	0
- Initial Investment Costs	(4,162)	(16,256)	0	0	(70,412)	76,814	0	0
+ Recovery of Working Capital		0	0	0	0	0	0	0
+ Salvage Value		0	0	0	(5,738)	2,375	0	0
After-Tax Cash Flow	4,162	21,139	(1,966)	5,562	72,592	(105,726)	32,164	0
Cumulative Cash Flow	4,162	25,301	23,335	28,897	101,489	(4,237)	27,927	27,927
Discounted Cash Flow	4,162	18,874	(1,567)	3,959	46,133	(59,992)	16,295	0

Figure 15 – Discounted Cash Flow for Passive Bioventing (Alternative Scenadio 1) vs. Conventional Bioventing (Base Scenario)

Using the discounted cash flow method results in a potential savings of $28,726 over a 5 year period if passive bioventing was installed instead of the conventional bioventing system.

Section 6: Implementation Issues

While the costs are lower, the time period for remediation with the passive system is longer (4 years compared to 3 years) which may not be acceptable at some sites. This time period extension was primarily needed due to the use of a design radius of influence based on declining respiration rates.

In general, the point at which the cost to install any 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 upon:

- differences in the radius of influence between conventional and passive bioventing;
- cost to install electric power;
- local utility costs;
- drilling costs (affected primarily by contamination depth, soil type, and location); and,
- the time frame needed to achieve remedial goals.

The most difficult factor to predict is the difference in radius of influence between conventional bioventing and passive bioventing. An empirical relationship was developed as part of the USAF Bioventing Initiative to relate pressure response from a short one-day air permeability test to radius of influence for conventional bioventing design purposes (see Section 1.5 of Volume II from USEPA ORD, 1995). Site cleanup times are also difficult to predict, even with conventional bioventing, but are primarily a function of the microbial respiration rate, achievable air flow, contaminant concentrations, and soil porosity (see Section 1.4 and Section 3 of Volume II from USEPA ORD, 1995). Therefore, simple inexpensive tests (air permeability and *in situ* respiration tests) are already available to predict the conventional radius of influence and monitor site cleanup progress.

The only factor remaining is the radius of influence for the passive system. The demonstration data supports the use of short-term natural air flow measurements and a recasting of the equation presented in Section 2.2 of Volume II from USEPA ORD, 1995 (where it is used to size blower systems) to determine a radius of influence for a passive system. The demonstration study's validation of this equation to predict the radius of influence, and therefore estimated costs, for a passive bioventing system is a significant success. Therefore, using relatively inexpensive, short-term airflow measurements alone, a cost comparison between passive and conventional bioventing can now be conducted with some confidence.

6.1 Lessons Learned. The following lessons were learned during implementation of this demonstration:

1) Difficulty of site selection. Site selection for this demonstration was a time-consuming process. Reasons for this included:

   a) Initially focusing on sites which appeared to have very limited application of the technology (i.e., tidally-influenced sites).

b) Limited information was often available to adequately screen sites with a degree of confidence that the site would meet the demonstration objectives (i.e., have adequate airflow). Therefore, additional time was spent visiting multiple candidate sites and collecting pre-demonstration data (e.g., airflow).

The authors wish to emphasize the importance of partnering for demonstrations. Partnering can help to overcome site selection difficulties by providing access to personnel and resources, which would otherwise be unavailable.

Another, but nevertheless important factor which made site selection difficult was that petroleum sites are now often considered "low priority" sites or often have undergone some degree of remediation. Notably, in contrast to this deficiency as a demonstration site characteristic, these sites could be excellent candidates for sites where conventional systems could be turned off in favor of long-term operation in a passive mode.

2. Passive valve construction. The passive valve originally was constructed using single-cell foam rubber for the internal seal and it did not perform as well as mylar. If the design shown on Figure 2 is used, mylar should be used for the seal. In addition, users should note that there is now commercially available an off-the-shelf passive valve called the “BaroBall” developed by Savannah River Site researchers. The BaroBall valve was not evaluated or used during this demonstration.

3. Oxygen sensors. The directly-buried oxygen sensors provided good quality data and were relatively simple to install using standard hollow-stem auger techniques. It is strongly recommended that the sensors with the integrated pressure measurement and sampling port (as used during this demonstration) also be used for any future installations since it allows 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, ISR tests can be performed unattended.

4. Verticality of boreholes. The verticality measurements indicated that deviations of as much as 1 to 2 feet could be expected at borehole depths of 50 to 60 feet bgs using hollow stem auger techniques. This information should be used to determine if verticality measurements are required at sites where precise radius of influence measurements is needed.

5. Relative humidity. Relative humidity measurements were not collected during this demonstration. It should be added to the list of measured parameters for future passive bioventing demonstrations so that the relationship between relative humidity, ambient temperature, and barometric pressure changes can be evaluated.

6. Reduced iron and ORP. Although the reduced iron and ORP measurements were of some use during the demonstration, since these are measurements not typically collected at bioventing sites, there is not a large data set against which to compare the results. The data collected during this demonstration indicated that despite very anaerobic conditions, the potential for significantly reduced iron or highly reduced soils to exert a significant oxygen demand was relatively low.

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