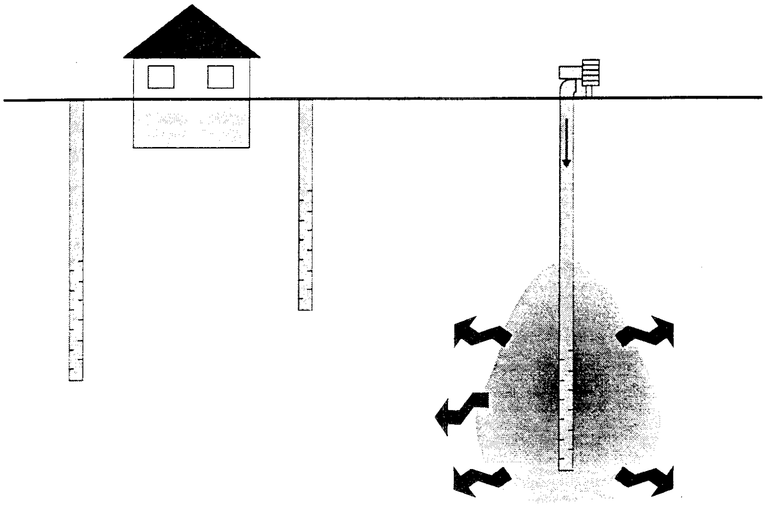
Bioventing
Performance and Cost Results From Multiple Air Force Test Sites



Technology Demonstration
Final Technical Memorandum

June 1996

Air Force Center for Environmental Excellence
Technology Transfer Division
Brooks AFB, Texas

BIOVENTING PERFORMANCE AND COST RESULTS FROM MULTIPLE AIR FORCE TEST SITES TECHNICAL DEMONSTRATION TECHNICAL MEMORANDUM

FINAL

Prepared for the
AIR FORCE CENTER FOR ENVIRONMENTAL EXCELLENCE
TECHNOLOGY TRANSFER DIVISION
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EXECUTIVE SUMMARY

This technical memorandum summarizes the results of bioventing treatability tests conducted at multiple Air Force sites. In April 1992, the Air Force Center For Environmental Excellence (AFCEE), in cooperation with the Air Force Armstrong Laboratory and US Environmental Protection Agency (EPA), began a major initiative to demonstrate the feasibility of using the bioventing technology on over 145 Air Force sites nationwide. This significant research initiative has now been completed, and the results are summarized in this technical memorandum.

Test Objectives

Four key objectives were established for this initiative.

- To document the ability of bioventing technologies to remediate petroleum-contaminated soils in a variety of climatic, soil, and contaminant conditions.
- To use this significant data set to complete a bioventing principles and practices manual for use by the Air Force, the Department of Defense (DOD), EPA, and other interested agencies.
- To promote regulatory and public acceptance of this technology.
- To begin the process of effectively remediating 145 fuel-contaminated sites at minimum cost to the taxpayer.

Results and Conclusions

- Bioventing was found to be effective under a wide variety of soil and climatic conditions.
- Based on soil sampling data from over 100 sites, an average BTEX reduction of 97 percent was achieved during the first year of testing.
- The average cost for design, installation, and 1-year of operation and monitoring at a single vent well bioventing site was less than $60,000 per site based on actual costs incurred at the test sites.
- Regulatory acceptance of this technology was obtained in 38 states and all 10 EPA regions. The Air Force bioventing initiative has greatly accelerated the use of this technology in the private sector.
- At nearly half of the sites tested, the pilot systems have been converted into full-scale remediation systems saving the Air Force an estimated $5M - $10M in design and construction costs.
- At the majority of these sites, the reductions in BTEX achieved during the first year of bioventing are sufficient to meet the most conservative EPA risk-based cleanup criteria for soils.

Recommendations

- Due to the widespread success of the bioventing technology and its low cost, it should be considered the preferred remedy for jet and diesel fuel spills at DOD sites. With proper safety precautions, bioventing can also be used to remediate gasoline-contaminated sites.
- All remediation contractors working for DOD should be required to consider bioventing before recommending more complicated or expensive alternatives for fuel-contaminated sites.

1 PROJECT OVERVIEW

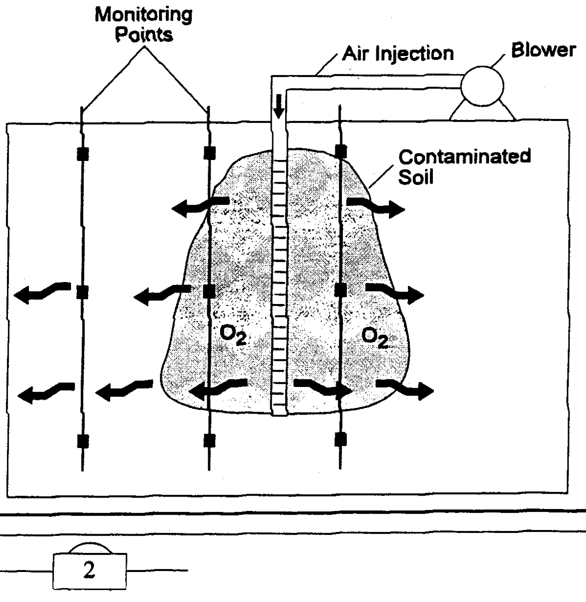
Technology Summary

Bioventing is a proven technology that stimulates the natural *in situ* biodegradation of petroleum hydrocarbons in soil by providing oxygen to existing soil microorganisms. In contrast to soil vapor extraction, bioventing utilizes low air flow rates to provide only enough oxygen to sustain microbial activity. Oxygen is most commonly supplied through direct air injection into residual vadose-zone soil contamination, as illustrated in Figure 1. In addition to degradation of adsorbed fuel residuals, volatile compounds also are biodegraded as vapors move slowly through biologically active soil.

Although this technology was first applied by the Dutch engineers J. Van Eyk and Vreeken (1988), Air Force researchers have made significant advancements in the understanding of soil microorganism processes and *in situ* monitoring techniques. During the past 5 years, over 30 scientific publications on this subject have been authored by Air Force sponsored researchers, including a *Test Plan and Technical Protocol For Bioventing,* which has been distributed to over 1,500 DOD environmental managers and their consultants to standardize bioventing procedures (Hinchee *et al.*, 1992). The protocol was reviewed and endorsed by EPA's Risk Reduction Engineering Laboratory. In a letter to EPA Regional Administrators, the Deputy Assistant Administrator of EPA's Office of Solid Waste and Emergency Response supported the protocol and requested that EPA regions cooperate with the Air Force in nationwide testing. Recently, the Air Force published a comprehensive design manual based on results of this national test program (Leeson and Hinchee, 1995).

The Air Force investment in this technology has been driven by the need to remediate an estimated 2,000 petroleum-contaminated sites located throughout the United States. Bioventing has widespread potential application because soil microorganisms are capable of degrading a wide variety of petroleum products, including JP-4 jet fuel, gasoline, diesel fuel, and heating oils. *In situ* treatment of fuel contaminants in soils greatly reduces the expense and disruption associated with traditional excavation and treatment/disposal methods. Moreover, *in situ* bioventing eliminates expensive off-gas treatment often required with conventional soil vapor extraction systems, and can reduce remediation costs by as much as 50 percent at sites where vapor emissions must be treated (Reisinger *et al.*, 1993). The bioventing technology is mechanically simple and requires minimal maintenance, making it a cost-effective solution in an era of funding shortfalls and reduced manpower.

FIGURE 1. TYPICAL BIOVENTING SYSTEM

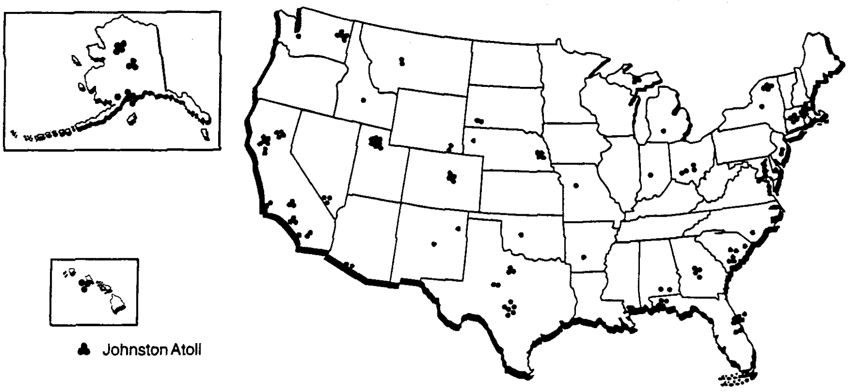


Test Site Locations

Between April 1992 and December 1995, initial bioventing tests were completed at 145 Air Force sites. Figure 2 illustrates the geographic and climatic diversity of test locations. With the endorsement of the EPA, bioventing has been approved for application in 38 states and in all 10 EPA regions. These sites are under CERCLA and RCRA jurisdiction as well as regulated under special state underground storage tank (UST) programs.

FIGURE 2. AIR FORCE BIOVENTING INITIATIVE LOCATIONS

AS OF DECEMBER 1995



Following initial testing, extended bioventing systems were installed and operated at 123 sites on 56 Air Force installations. At 17 of the initial test sites natural aeration was sufficient to provide oxygen to contaminated soils without the aid of mechanical blowers. At five sites, regulatory delays or unsuitable site conditions resulted in cancellation of extended testing. Table 1 summarizes the overall progress of the bioventing initiative. Over half of the pilot systems continue to operate as full-scale site remediation system. In addition to the extensive field work, AFCEE has sponsored three technology transfer conferences attended by over 600 Air Force and DOD personnel and has encouraged bioventing development in the private sector through presentations at more than a dozen national conferences.

TABLE 1. BIOVENTING INITIATIVE SUMMARY

	No. of Bases	**No. of Sites**
Initial Site Visits	60	159
Completed Work Plans	59	150
Initial Testing Complete	56	145
One-Year Tests Underway	56	123
Natural Attenuation Only	8	17
Six-Month Respiration Tests	55	122
Final Soil Sampling	55	118

2 TESTING PROTOCOL

The testing protocol included six common tasks performed at each bioventing test site. Two contractors, Parsons Engineering Science, Inc. and the Battelle Memorial Institute, have been responsible for completing these bioventing tasks.

- Each test began with a site meeting and technology briefing to base officials and local regulatory agencies.
- A site-specific work plan was prepared describing where and how the test would be conducted. The generic *Test Plan and Technical Protocol for Bioventing* (Hinchee *et al.*, 1992) was provided as a supplement to the work plan to more completely describe test procedures.
- A preliminary soil gas survey was conducted to locate the area of depleted soil gas oxygen concentrations and to confirm that bioventing was required. Numerous sites were found to be naturally aerated. At these sites natural biodegradation is occurring without the aid of mechanical bioventing.
- Initial testing was completed to determine if site soils were permeable enough to allow distribution of oxygen (air) and to estimate the rate of fuel biodegradation. Initial soil and soil gas samples were collected and analyzed and an initial test report was provided to the base. If favorable conditions existed for bioventing, a small blower system was installed for a 1-year period of air injection.
- During the 1-year extended testing, *in situ* respiration rates and the radius of oxygen influence were monitored for each site. At many sites, the radius of oxygen influence from a single air injection well encompassed the entire contaminated soil volume, resulting in full-scale remediation.
- At the end of 1 year of extended testing, soils and soil gas were resampled to determine bioventing progress, and a letter was provided to the base recommending continued operation of the pilot-scale system, upgrading to a full-scale system, or in some cases, additional confirmatory soil samples to support site closure.

3 TEST RESULTS

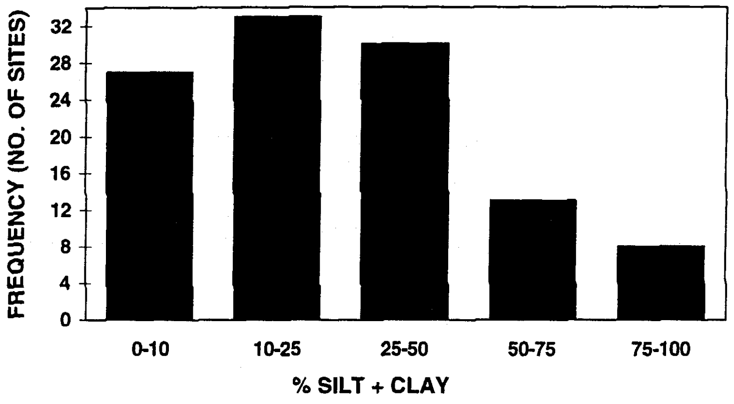
Overview

Initial test data from 145 sites revealed that bioventing has almost universal application for remediating hydrocarbon-contaminated soils. Successful bioventing is now underway at a wide variety of sites contaminated with gasoline, JP-4, diesel fuel, heating oils, and waste oils. A detailed statistical analysis was completed to determine what factors produce the highest rates of *in situ* biodegradation. While warm, moist soils are optimum for microbial growth, and have produced higher than average biodegradation rates, the most encouraging results have been obtained at sites with less than optimum conditions. A summary of initial site conditions and their apparent impact on the bioventing process is provided in this section.

Soil Gas Permeability Results

Soil grain size and soil moisture significantly influence soil gas permeability. A grain-size analysis was completed on several samples from each site. Figure 3 illustrates the relative distribution of fine-grained soils encountered at test sites. Sufficient soil gas permeability has been demonstrated at numerous sites with silt and clay contents exceeding 80 percent by weight (Downey *et al.*, 1992). Approximately 20 percent of the sites tested contain greater than 50 percent silt and clay fractions. Oxygen distribution was generally uniform in soils where darcy values exceed 0.1; limited data are available for soils with darcy values of less than 0.1. At approximately half of the sites tested, the radius of oxygen influence from a single vent well was equal to, or larger than the contaminated area. Continued bioventing at these sites should result in full-scale soil remediation. Perhaps the greatest limitation to air permeability was excessive soil moisture. A combination of high moisture content and fine-grained soils made bioventing infeasible at only two of the 145 test locations.

FIGURE 3. SOIL SILT AND CLAY CONTENT



Biodegradation Factors

Several soil characteristics that are known to impact microbial activity were investigated at each site. Among the most important factors are pH, moisture, basic nutrients such as nitrogen and phosphorus, and temperature. Soil pH measurements shown in Figure 4 indicate that the majority of bioventing initiative sites are slightly alkaline and fall within the acceptable pH range of 5 to 9 for microbial activity. However, microbial respiration was observed at all sites, even in soils with pH values that were outside of this optimal range.

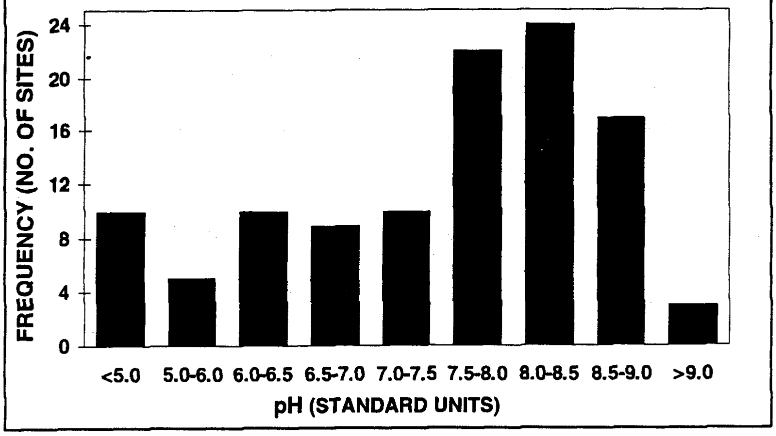


FIGURE 4. INITIAL SOIL pH

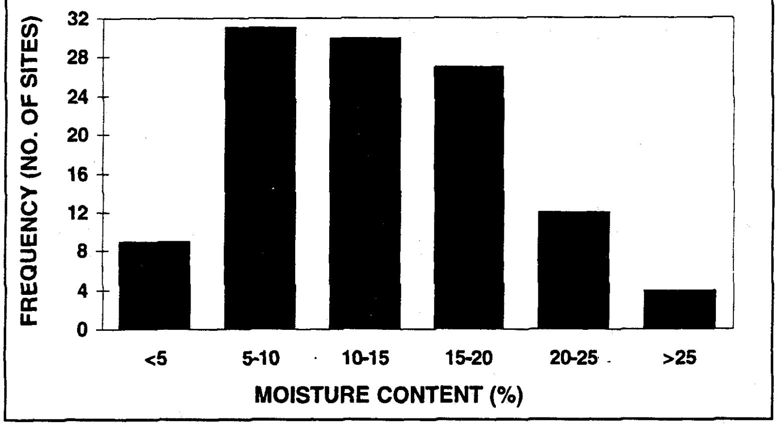
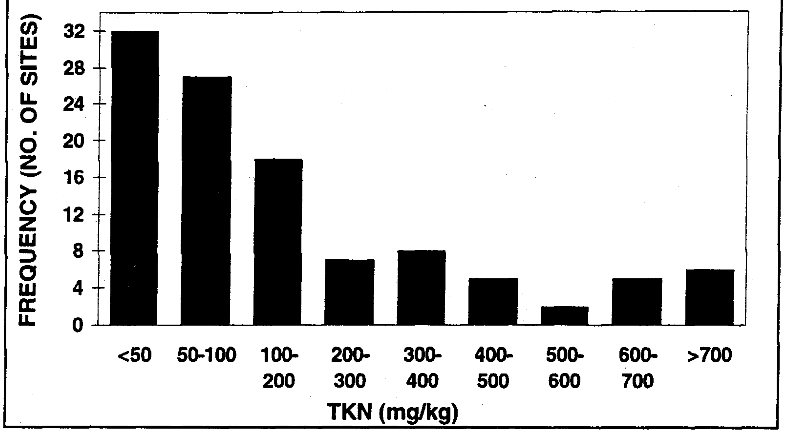


FIGURE 5. INITIAL SOIL MOISTURE

Soil moistures encountered at bioventing test sites are shown in Figure 5. Optimum soil moisture is very soil specific, and is an important bioventing test parameter because too much moisture can reduce the air permeability of the soil and decrease its oxygen transfer capacity. Too little moisture can inhibit microbial activity. Several test sites in semi-arid locations have sustained biodegradation rates with moisture levels as low as 3-5 percent by weight. However, biodegradation rates in more arid soils tended to be lower than in moist soils of similar temperature.

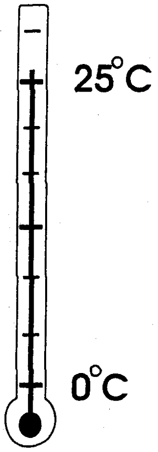
Figure 6 provides a summary of total Kjeldahl nitrogen (TKN) concentrations in test site soils. Natural nutrient levels as low as 20 mg/kg TKN and 3 mg/kg total phosphorus were sufficient to sustain biological respiration at sites when the most limiting element, oxygen, is provided. A major question addressed by this test initiative, and supporting statistical analysis, was the impact of high natural nutrient levels on initial respiration rates. A multivariable statistical analysis completed by Battelle (Leeson *et al.*, 1995) indicated only a slight correlation between high natural TKN levels and higher respiration rates.

FIGURE 6. INITIAL SOIL TOTAL KJELDAHL NITROGEN



Controlled nutrient additions to the subsurface at both Tyndall AFB (Miller and Hinchee, 1990) and Hill AFB (Dupont *et al.*, 1991) test sites resulted in little apparent increase in hydrocarbon biodegradation rates. Although bench-scale testing generally shows increased biological activity when nutrients are added, the benefits of nutrient addition for *in situ* bioventing systems has yet to be demonstrated.

A frequency chart is not provided for soil temperature; however, thermocouples were installed at several depths at all sites to monitor seasonal temperature changes and their impact on respiration rates. Biological activity has been measured at Eielson AFB, Alaska in soil temperatures as low as 0°C (Sayles *et al.*, 1992a). Previous research has shown that the van't Hoff-Arrhenius equation provides a good estimate of temperature effects on soil microbial activity (Miller and Hinchee, 1990). This relationship predicts a doubling of microbial activity for every 10°C increase in temperature. Bioventing will more rapidly degrade fuel residuals during summer months, but some remediation still occurs at soil temperatures down to 0°C.

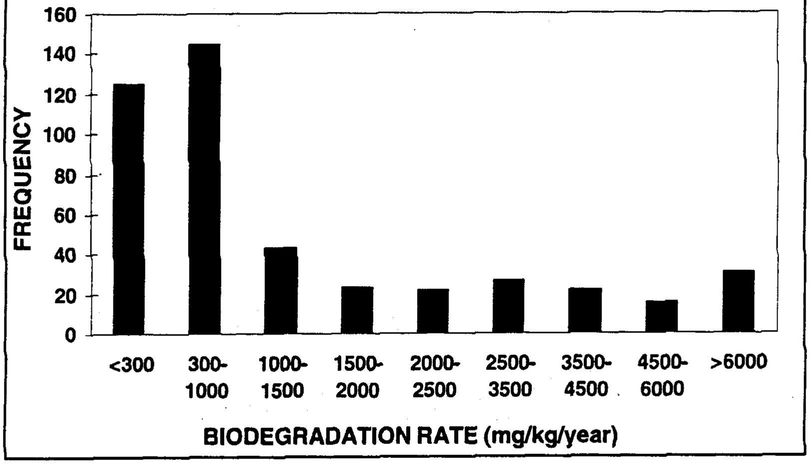


In situ biodegradation has been observed in soil temperatures between 0°C and 25°C.

Rates of Biodegradation

A key indicator of *in situ* biological activity and fuel biodegradation is oxygen consumption. Using a conservative stoichiometric oxygen demand of 3.5 mg of oxygen for every milligram of hydrocarbon degraded, oxygen utilization can be converted into milligrams of fuel biodegraded per kilogram of soil. Figure 7 illustrates the wide variation in estimated fuel biodegradation rates occurring at over 400 individual monitoring points. Based on this large data set, an average initial biodegradation rate of 1,200 mg/kg/yr was measured at the Air Force test sites. Following 1 year of bioventing the average biodegradation rate at these sites had decreased to 700 mg/kg/yr. This reduction in biodegradation rate is primarily the result of decreasing bioavailability of fuel hydrocarbons over time.

FIGURE 7. INITIAL BIODEGRADATION RATES



Bioventing for Risk Reduction

In situ respiration testing provides an estimate for the total petroleum hydrocarbons (TPH) that can be biodegraded during each year of bioventing operation. Regulatory emphasis has recently shifted toward removal of specific chemical compounds that can pose a risk to human health or the environment. Benzene, toluene, ethylbenzene, and xylenes (BTEX) compounds are the most mobile and toxic components found in most fuels and are the focus of risk-based fuel remediation projects. Fortunately, these compounds are relatively easy to biodegrade, and remediation times can be significantly reduced when risk-based, BTEX cleanup criteria are established.

Tyndall AFB pilot test data, shown in Figure 8, illustrates how the BTEX fraction was removed preferentially compared to total recoverable petroleum hydrocarbon (TRPH) during this 200-day pilot test (Miller and Hinchee, 1990). The ability of bioventing to preferentially remove benzene and other aromatics makes this technology well-suited for risk-based remediations. Figure 9 illustrates the average TPH and BTEX removal achieved in soils and soil gas after 1 year of bioventing based on 328 sampling locations at over 100 sites. The average soil TPH reduction achieved during the first year of bioventing was approximately 24 percent, while the average total BTEX reduction was approximately 97 percent. The average BTEX reduction in soil gas was approximately 85 percent.

FIGURE 8. AVERAGE REDUCTIONS IN SOIL CONTAMINANTS

JP-4 Spill - Tyndall AFB, Florida

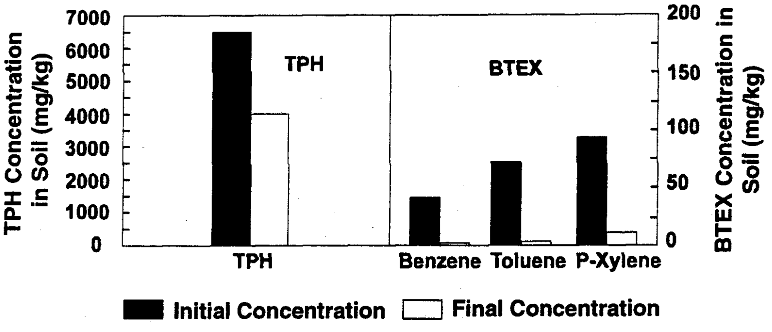
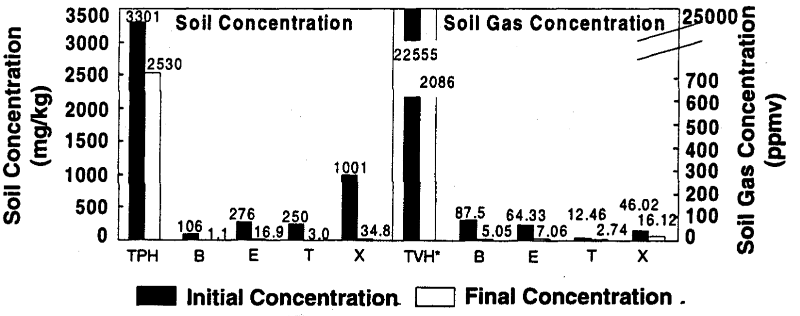


FIGURE 9. AVERAGE TPH AND BTEX CONCENTRATIONS: INITIAL AND 1-YEAR RESULTS



* Total Volatile Hydrocarbons

Volatilization During Bioventing

One important advantage of bioventing is that it produces little or no release of hydrocarbons into the atmosphere. Because air is injected into the soil at low flow rates, soil gas is displaced horizontally, and the volatile hydrocarbons are biodegraded as the soil gas moves slowly through the soil. Vapor biodegradation has been confirmed in pilot testing at Hill AFB (Sayles *et al.*, 1992b), and flux testing has been conducted at five other sites to measure potential surface emissions. The estimated volatile hydrocarbon flux to the atmosphere and maximum initial soil gas hydrocarbon concentrations at these sites are shown in Table 2. To date, the maximum surface emission that has been observed is 250 mg/day/m^2. Rates of biodegradation are typically 100 times the rates of volatilzation from these sites. In some situations, such as shallow soils contaminated with gasoline, air injection could produce unacceptable vapor migration or surface emissions. At these sites, soil vapor extraction and vapor treatment are generally recommended to reduce high fuel vapor concentrations before air injection bioventing can be used. On some gasoline-contaminated sites, pulsed air injection, or vapor extraction with recirculation into perimeter soils, have provided less expensive solutions for vapor control and treatment (Downey *et.al.*, 1995).

TABLE 2. RESULTS OF FLUX MONITORING AT BIOVENTING SITES

Base	Site Type	Air Injection Rate (scfm)	Screen Depth (ft)	TVH Flux Estimate (mg/day/m^2)	Initial Soil Gas TVH (ppmv)
Plattsburgh AFB, NY	Fire Training Pit	13	10-35	160	8,400
Beale AFB, CA	Fire Training Pit	30	10-25	100	4,800
Bolling AFB, CA	Diesel Spill	20	10-15	250	860
Fairchild AFB, WA	JP-4 Spill	15	5-10	250	29,000
McClellan AFB, CA	Diesel Spill	50	10-55	25	380

4 BIOVENTING CASE STUDIES

The following case studies provide a snapshot of the progress to date at several pilot- and full-scale bioventing sites. Currently 17 of the original bioventing test sites have achieved closure status, and another 20 sites are in the closure process.

Hill AFB, Utah, Building 914 Site

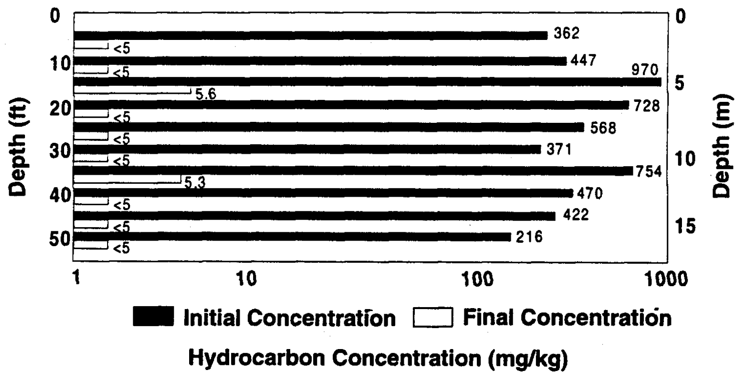
Site Description: A spill of approximately 25,000 gallons of JP-4 contaminated soils to a depth of approximately 60 feet. Soils are predominantly fine sands with occasional clay stringers. Regional groundwater is over 600 feet deep, and average soil moisture is less than 6 percent.

Bioventing System Installed: A full-scale soil vapor extraction system was originally installed at the site. This 15-well system operated for 9 months and was then converted into a bioventing system by reducing extraction rates by over 70 percent. The system was operated in the bioventing mode for an additional 9 months, saving over $54,000 in off-gas treatment costs.

Biodegradation Rates: During extraction, oxygen, carbon dioxide, and hydrocarbon concentrations were monitored in the off-gas. Based on this data, an estimated 110,000 pounds of fuel were volatilized, and 90,000 pounds were biodegraded during the total 18-month demonstration.

Soil Remediation Achieved: Initial soil samples showed JP-4 concentrations as high as 20,000 mg/kg, with an average of approximately 400 mg/kg. Soils were resampled after the initial 9 months of vapor extraction, and again after 9 months of bioventing. Figure 10 illustrates the 98-percent reduction in fuel contamination achieved during the 18-month demonstration. Following this demonstration, the State of Utah approved the closure of this site.

FIGURE 10. HILL AFB (BUILDING 914) SOIL SAMPLE RESULTS



Kelly AFB, Texas, Site FC-2

Site Description: This site was used from the 1950s to 1981 for fire training exercises. Several times each year, waste petroleum, oils, and lubricants (POL) and fuel fires were set and extinguished around a simulated airplane at the center of the site. No containment system was used to prevent direct infiltration of POL and fuel into the soils, which are comprised of gravelly clay. Groundwater occurs 15 -18 feet below the ground surface.

Bioventing Pilot System: A single air injection well and four vapor monitoring points were installed at the site in December 1992. An air injection rate of approximately 10 standard cubic feet per minute (scfm) produced a radius of oxygen influence of at least 50 feet.

Biodegradation Rates: An average initial biodegradation rate of 2,750 mg of fuel per kg of soil per year was estimated based on initial, 6-month, and 1-year test results.

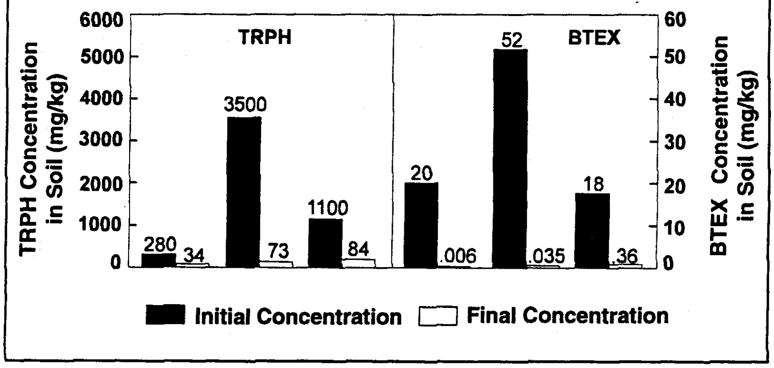
Soil Remediation Achieved: Several soil and soil gas samples were collected after 1 year of bioventing treatment. Figure 11 illustrates the removal of BTEX and TRPH from soils achieved to date. Due to the low concentrations of BTEX remaining in these soils, they are no longer a source of significant groundwater contamination.

Full-Scale Upgrade: Based on successful pilot testing, a full-scale system consisting of six vent wells has been installed at the site to complete the remediation of an estimated 30,000 cubic yards of contaminated soil.

Cost: The total cost of the initial 1-year pilot testing and full-scale system upgrade at this site was $115,000.00 (approximately $3.80/cubic yard). This cost includes:

Work Plans/Regulatory Approval	$5,000
Design	$9,000
Equipment Cost	$3,500
Installation	$62,500
1-Year Maintentance/Monitoring	$9,000
Reporting/Profit	$26,000

FIGURE 11. KELLY AFB (SITE FC-2): 1-YEAR RESULTS



US Coast Guard Support Center Kodiak, Alaska, Site 6B-Fuel Farm (Tank 191)

Site Description: In order to assist in the transfer of this technology to other government agencies, AFCEE sponsored bioventing demonstrations at several DOD sites. A site at the Kodiak Island Coast Guard Support Center was selected to demonstrate this technology at a remote northern facility. Installed in the early 1940's, Tank 191 is a concrete and steel, 567,000-gallon underground storage tank (UST) previously used for storage of diesel and JP-5 jet fuel. The tank was abandoned in 1978 due to significant leakage.

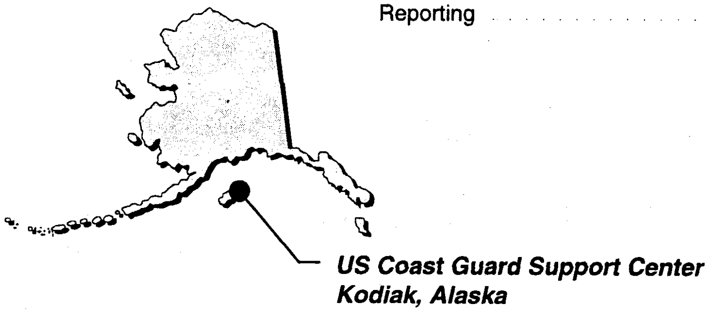
Bioventing Pilot System: One air injection vent well and two vapor monitoring points were installed in the sand and gravel fill surrounding the tank in August 1994. An air injection flow rate of 26 standard cubic feet per minute (scfm) produced a radius of oxygen influence of 90 feet in soils surrounding the tank. Groundwater was encountered at approximately 15 feet below ground surface (bgs) during system installation. Approximately 4,500 cubic yards were treated by this pilot system.

Biodegradation Rates: Although soil temperatures at the site averaged only 6°C, an average biodegradation rate of 1,300 mg fuel per kg soil per year was estimated based on initial, 6-month, and 1-year respiration test results.

Soil Remediation Achieved: Soil and soil gas samples were collected prior to pilot testing and after 1 year of extended testing. Diesel-range total extractable petroleum hydrocarbons (TEPH) were reduced more than 80 percent on average during the 1-year test, and 1-year total BTEX concentrations in soil measured less than 0.5 mg/kg, making the site a good candidate for risk-based closure.

Cost: The total cost of system installation and 1 year of pilot testing at this remote site was $69,000 ($15.30/cubic yard), approximately 25 percent higher than the average cost of bioventing system installation and 1 year of testing in the lower 48 states. Additional costs are primarily due to higher transportation and drilling costs in remote locations. Costs include:

Work Plans/Regulatory Approval	$7,200
Mobilization and Site Preparation	$11,300
Installation of Pilot System	$29,700
1-Year Maintentance/Monitoring	$11,100
Reporting	$9,700



5 COST ANALYSIS

Based on Air Force and recent commercial applications of this technology, the total cost of *in situ* soil remediation using the bioventing technology is $10 to $60 per cubic yard. At sites with over 10,000 cubic yards of contaminated soil, costs of less than $10 per cubic yard have been achieved. Costs greater than $60 per cubic yard are associated with smaller sites (<500 cubic yards), but bioventing can still offer significant advantages over more disruptive excavation options. Operations and maintenance (O&M) costs are minimal, particularly when base personnel perform simple system checks and routine maintenance (e.g., change air filters). Table 3 provides a more detailed cost breakdown for remediation of a typical Air Force site with 5,000 cubic yards of soil contaminated and an average soil concentration of 3,000 mg/kg of JP-4. Additional cost and pilot system data are included as an Appendix.

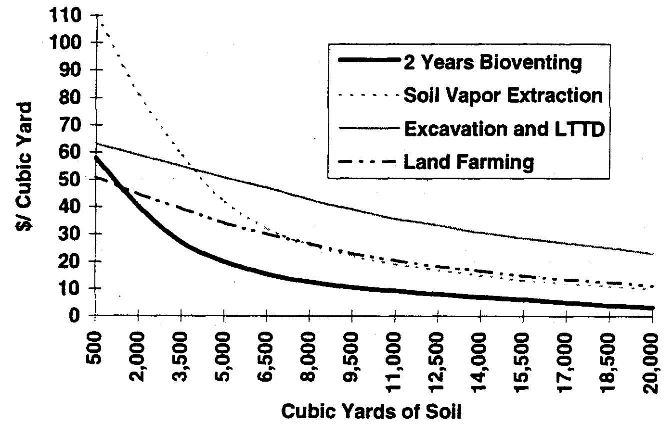
Figure 12 provides a comparison of estimated unit costs for several technologies commonly used for remediating fuel-contaminated soils. All costs are based on the treatment of soil contaminated with 3,000 mg/kg of JP-4. Costs are provided for the following remediation scenarios: 2 years of *in situ* bioventing (includes all tasks shown in Table 3); excavation and 1 year of on-base landfarming with leachate controls; 1 year of soil vapor extraction with thermal vapor treatment; and excavation followed by off-site low-temperature thermal desorption (LTTD). The cost of reconstructing excavated areas is not included. At many sites with contamination beneath concrete and buildings, bioventing is the only cost-effective treatment option.

TABLE 3. TYPICAL FULL-SCALE BIOVENTING COSTS

Task	Total ($)
Site Visit/Planning	5,000
Work Plan	5,000
Pilot Testing	27,000
Regulatory Approval	3,000
Full-Scale Construction	
Design	7,500
Drilling/Sampling*	15,000
Installation/Start Up	5,000
Two-Year Monitoring	8,500
Two-Year Power	2,800
Soil Sampling at Two Years	13,500
Total	92,300

* Assumes four air injection wells drilled to depth of 15 ft.

FIGURE 12. COMPARISON OF UNIT COSTS*



* Bioventing costs are based on expenses incurred during the AFCEE Bioventing Initiative. Other technologies are based on vendor information.

6 LESSONS LEARNED

Application

- Initial bioventing tests were successfully completed at 142 of the 145 test locations. At two sites, excessive soil moisture and clay made it impossible to inject air and supply oxygen. At a third site in the desert, biodegradation rates were too low for bioventing to be practical as the primary remediation method.

- Air injection was the preferred method of oxygen supply. Vapor extraction was used at five gasoline-contaminated sites to reduce the potential of uncontrolled vapor migrations. After several months of vapor extraction, systems at these sites were converted to air injection bioventing.

- Bioventing was successfully applied at sites contaminated with a variety of petroleum products, including JP-4, gasoline, diesel fuel, waste oils, Stoddard® solvents, and hydraulic fluids.

- The feasibility of bioventing at any site will be determined during pilot testing by answering these two questions:

  - Is the soil sufficiently permeable to provide a miminum of 5 percent oxygen to the entrie contaminated soil volume?

  - Is the initial biodegradation rate sufficient to cost effectively reduce contaminants of concern?

Performance

- Based on initial respiration testing, an average initial biodegradation rate of 1,200 milligrams of fuel per kilogram of soil per year was measured at the Air Force test sites. Rates of biodegradation generally decreased at each site over time as the most biodegradable compounds were consumed first, leaving the more recalcitrant organics to degrade at a slower rate.

- Successful bioventing pilot tests were completed in extreme climates from the interior of Alaska to the deserts of southern California. Higher biodegradation rates were generally measured in warmer soils, but soil microbes were capable of biodegradation at temperatures approaching 0°C.

- Based on soil sampling data from over 100 sites, an average BTEX reduction of 97 percent was achieved during the first year of bioventing. On the average, TPH was reduced 24 percent. The preferential removal of toxic compounds such as benzene makes bioventing an excellent low-cost, risk-reduction technology.

- Regulatory acceptance of this technology was obtained in 38 states and all 10 EPA regions where bioventing tests were completed.

- The cost of bioventing ranges from less than $10 to approximately $60 per cubic yard of soil treated. At sites with over 10,000 cubic yards, costs of less than $10 per cubic yard are common, while sites with less than 500 cubic yards may experience costs of over $60 per cubic yard. Even at small sites, bioventing is less disruptive than excavation and can treat soils beneath buildings and other valuable structures.

7 RECOMMENDATIONS

The Air Force bioventing initiative has demonstrated that this technology is effective at reducing BTEX and TPH concentrations under varying site conditions. Initial testing has been completed at 145 sites, with 123 pilot systems installed on 56 Air Force installations. On smaller test sites, many of these single-well pilot systems are actually providing full-scale remediation. On larger sites, successful pilot systems should be expanded to full-scale systems to complete site remediation. Due to its simplicity, low cost, and minimum O&M requirements, bioventing is particularly well suited for an era of reduced DOD manpower and funding, and for sites located on bases scheduled for closure.

All DOD remediation contractors should be required to consider bioventing as a preferred remedy for fuel-contaminated soil before recommending more expensive alternatives. Bioventing should play a significant role in achieving the Air Force's goal of initiating cost-effective cleanup at all petroleum-contaminated sites by the year 2000.

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APPENDIX

Additional Cost and System Construction Information on AFCEE Bioventing Initiative Sites

TABLE A
SUMMARY OF AFCEE BIOVENTING INITIATIVE
INSTALLED PILOT TEST SYSTEMS

BASE	SITE	NUMBER OF VMP'S[a/]	NUMBER OF VENT WELLS	VENT WELL (VW) IDENTIFIER	VW SCREENED INTERVAL [b/] (feet)	TREATMENT VOLUME[p/] (Cubic Yards)	BLOWER SIZE AND TYPE	COST [d/]
FE WARREN AFB, WY	FTA-1	3	1	VW	3 - 8	800	3 HP Positive Disp.	
	SITE 1 (SPILL SITE)	3	1	VW	8 - 13	2,000	3 HP Positive Disp.	$53,545.30
HILL AFB, UT	BLDG 924	6	1	HVW [f/c/]	100 feet long/12 ft. deep	3,000	2 HP Regenerative	
	BLDG 204.1	3	1	VW [f/]	10 - 50	2,300	1 HP Regenerative	
	BLDG 228	1	1	VW [f/]	10 - 40	7,500	1 HP Regenerative	
	BLDG 214	2	1	VW [f/]	5 - 60	11,200	1 HP Regenerative	
	SITE 40002	2	1	VW [f/]	5 - 45	2,100	1 HP Regenerative	
	SITE 1705	2	1	VW [f/]	10 - 20	900	1 HP Regenerative	
	SITE 510.8	3	1	VW	34 - 64	4,700	1 HP Regenerative	
	SITE 388	5	2	VW1 [f/]	25 - 75	46,000	2 HP Regenerative	
				VW2	55 - 120			$201,171.10
OFFUTT AFB, NE	LPD (BLDG 528)	3	1	VW	3.5 - 8.5	900	1 HP Regenerative	
	BLDG 30 SITE	3	1	VW	3.5 - 8.5	600	1 HP Regenerative	
	BLDG 406 (2 YR)	3	4	VW1 - VW4	6 - 16	12,000	2 HP Regenerative	
	POL AREA	3	1	VW	7.5 - 12.5	1,300	1 HP Regenerative	$233,304.55
PLATTSBURGH AFB,NY	FTP-3	3	1	VW	6 - 36	15,100	2 HP Regenerative	
	FTP-2	3	1	VW	10 - 35	14,700	Manifolded to FTP-3	
	FTP-1	3	1	VW	10 - 45	18,900	2 HP Regenerative	
	FTP-4	3	1	VW	6 - 36	15,100	2 HP Regenerative	$207,372.00
K.I. SAWYER AFB, MI	POL AREA (ST-04)	3	1	VW	14 - 69	29,900	2 HP Regenerative	
	FT AREA(06)	3	1	VW	10 - 65	27,300	2 HP Regenerative	
	FT AREA(07)	3	1	VW	10 - 60	14,100	2 HP Regenerative	$153,057.05
BATTLE CREEK ANGB, MI	IRP Site 3 FTA	3	1	VW	10 - 30	8,700	1 HP Regenerative	$44,952.95
MCGUIRE AFB, NJ	JP-4 PIPELINE SS	3	1	VW	5 - 15	2,800	1 HP Regenerative	$69,863.05
TINKER AFB, OK	POL STRG AREA C	3	1	VW	7 - 17	1,800	1 HP Regenerative	$47,707.10
AFP 4, TX	FSA-1	3	1	VW	8 - 23	1,100	1 HP Regenerative	
	FSA-3	3	1	VW	5 - 15	700	1 HP Rotary Vane	$72,882.90
DYESS AFB, TX	FT40	4	1	VW	6.9 - 16.5	800	1 HP Regenerative	
	FT41	3	1	VW	6.4 - 16	1,200	1HP Regenerative	$59,809.45
KELLY AFB, TX	FC-2 (FTA)	3	6	VW	7 - 19	30,000	2 HP Regenerative	
	S-4 (JP-4 SPILL)	3	1	VW	7 - 17	1,800	1 HP Regenerative	
	BLDG 2093 [g/]	3	1	VW	7 - 17		1.5 HP Rotary Vane	
	D-10	3	1	VW	6 - 16	1,200	1 HP Regenerative	$158,758.00
BEALE AFB, CA	IRP SITE 3	4	1	VW	9.5 - 23.9	7,000	2 HP Regenerative	
	IRP SITE 18	3	1	VW	10 - 60	17,500	2 HP Regenerative	
	IRP SITE 11	3	1	VW	10 - 50	17,600	1 HP Regenerative	$201,535.65

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BASE	SITE	NUMBER OF VMP'S[a/]	NUMBER OF VENT WELLS	VENT WELL (VW) IDENTIFIER	VW SCREENED INTERVAL [b/] (feet)	TREATMENT VOLUME[c/] (Cubic Yards)	BLOWER SIZE AND TYPE	COST [d/]
TRAVIS AFB, CA	IRP SITE 1	4	1	VW	5 - 12	600	1 HP Regenerative	$97,565.45 [h/]
VANDENBERG AFB, CA	BASE SERV STAT.	4	5	VW	4.7 - 12	16,000	2 HP Regenerative	$330,295.90 [i/]
	SITE 6454	3	1	VW	5 - 70	13,000	1 HP Regenerative	
EDWARDS AFB, CA	IRP SITE 16 (JP-4)	3	1	VW	8 - 13	1,700	1 HP Regenerative	$145,839.25
	IRP SITE 21 (JET)	3	1	VW	7 - 14.5	2,400	1 HP Regenerative'	
	SITE 43(D.T.)	1	1	VW	4.5 - 15	200	1 HP Regenerative	
MARCH AFB, CA	IRP SITE 35C	3	1	VW	4 - 11	1,200	1 HP Rotary Vane	$98,047.10 [h/]
LA AFB, CA	BLDG 125	1	1	VW	7 - 37.5	1,700	1/10 HP Rotary Vane	$152,790.05 [h/]
	BLDG 241	3	1	VW	10 - 40.5	2,900	1 HP Regenerative	
	GATE 3	3	1	VW	14.5 - 55	16,000	1 HP Regenerative	
CAPE CANAVERAL, FL	FTA-2	4	3	VW	3 - 8	2,500	1 HP Regenerative	$150,712.95
	FAC 44625 D UST	3	1	VW	3 - 8	800	1 HP Regenerative	
	FAC 44625 E UST	3	1	VW	3 - 8	800	1 HP Regenerative	
	FAC 1748 UST	4	1	VW	3 - 8	800	1 HP Regenerative	
PATRICK AFB, FL	FTA-2	5	1	HVW	20 ft. long/3.5 ft.deep	600	1 HP Regenerative	$167,998.50 [i/]
	BX SERV. STAT.	5	1	HVW	30 ft. long/3.5 ft.deep	750	1 HP Regenerative	
CHARLESTON AFB, SC	FTA-03	4	1	HVW	20 ft. long/3.5 ft.deep	600	1 HP Regenerative	$138,320.00 [h/]
	JP-4 (BLDG 93)	4	2	VW1 & VW2	5.3 - 11.6	1,000	1 HP Regenerative'	
HICKAM AFB, HI	AREA H	3	1	VW	9.5 - 19.5	1,400	1.5 HP Rotary Vane	$182,137.15
	AREA K	3	1	VW	4.3 - 9.3	1,700	1.5 HP Rotary Vane	
	SITE 2 FSA	4	1	VW	15.75 - 45.75 and 65.75 - 100.75 [k/]	10,600	2 HP Regenerative	
AFP PJKS, CO	UST OTL	4	1	VW	5 - 20	2,100	1.5 HP Rotary Vane	$46,207.40
GRISSOM AFB, IN	JP-4 TRANS STAT.	5	8	VW1 - VW8	4-11.5	6,000	5.5 HP Regenerative	$88,303.90
RANDOLPH AFB, TX	TANK 20	3	3	VW1 - VW3	5 - 15	4,700	1.5 HP Rotary Vane	$45,743.00
KIRTLAND AFB, NM	FT-13	3	1	VW	5 - 30	3,100	1 HP Regenerative	$76,732.10 [h/]
BOLLING AFB, D. C.	BLDG 18	2	1	VW	6 - 21	3,900	1 HP Regenerative	$104,197.60
	FORMER TNK FM	6	4	VW1 - VW4	5 - 15	6,300	1& 5 HP Rotary Vanes	

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BASE	SITE	NUMBER OF VMP'S[a/]	NUMBER OF VENT WELLS	VENT WELL (VW) IDENTIFIER	VW SCREENED INTERVAL[b/] (feet)	TREATMENT VOLUME[p/] (Cubic Yards)	BLOWER SIZE AND TYPE	COST[d/]
MCCLELLAN AFB, CA	TANK FARM 2	3	1	VW	10 - 35	10,200	1 HP Regenerative	
	TANK FARM 4	3	1	VW	10 - 25	2,600	1 HP Regenerative	
	SA-6	2 (3)[l/]	(2)[l/]	VW1	25 - 100	7,300	2 HP Regenerative	
				VW2	15 - 100			
	PRL T-46	1	3	VW	8 - 45	8,400	1 HP Regenerative	
	DAVIS GCS	4	1	VW	10 - 55	14,100	1 HP Regenerative	
	CAPEHART GS	1 (8)[l/]	1	VW	10 - 105	19,600	1 HP Regenerative	$540,819.55[h/]
WESTOVER AFB, MA	BLDG 7701[m/]	3	1	VW	5 - 20	1,900	1 HP Regenerative	
	FA 7705	3	1	VW	6 - 21	3,900	1 HP Regenerative	$61,770.75
MALMSTROM AFB, MT	PH 2	3	1	VW	5 - 10	700	1.5 HP Rotary Vane	
	BFS	3	1	VW	5 - 10	700	1 HP Regenerative	$63,086.35
HANSCOM AFB, MA	BSS BLDG 1639[m/]	3	1	VW	4 - 7	2,300	1 HP Regenerative	
	BLDG 1812[m/]	3	1	VW	3.4 - 7	1,300	1 HP Regenerative	$43,281.55
FAIRCHILD AFB,WA	PS-1A	3	1	VW	4 - 8	1,900	1 HP Regenerative	
	PS-2	3	1	VW	5 - 10	1,900	1 HP Regenerative	
	PS-1B	3	1	VW	4.5 - 8.8	1,600	1 HP Regenerative	
	BLDG 2034	3	1	VW	5 - 10	1,300	1 HP Regenerative	
	BLDG 2035	3	1	VW	5 - 10	1,300	1 HP Regenerative	$290,124.55
ELMENDORF AFB, AK	ST 61	2	1	VW	5 - 20	3,700	1 HP Regenerative	
	VALVE PIT 3-4	2	1	VW	15 - 22	4,100	1 HP Regenerative	
	ST 71	2	1	VW	5 - 15	1,600	1 HP Regenerative	
	PH 3	2	1	VW	15 - 23	9,600	1 HP Regenerative	$147,879.40
ELLSWORTH AFB, SD	AREA D	3	2	VW1	10 - 17	1,800	1 HP Regenerative	
				VW2	5 - 10			
	BLDG 102	3	1	VW	8 - 18	1,900	1 HP Regenerative	$71,532.90
EGLIN AFB, FL	FTA HURLBURT	3	1	VW	2 - 7	700	1 HP Regenerative	
	EGLIN FTA	3	1	VW	5 - 40	11,600	2 HP Regenerative	$120,977.40
LITTLE ROCK AFB, AR	SS18	4	1	VW	3 - 10	1,000	1 HP Regenerative	$63,794.60
PEASE AFB, NH	AREA A	6	1	HVW	40 ft. long/7 ft. deep	800	5 HP Rotary Vane	
	AREA B	4	9	VW1 to VW9	5 - 15	14,000	5 HP Rotary Vane	$279,317.15
NELLIS AFB, NV	SITE 27	3	1	VW	55 - 25	7,300	1 HP Regenerative	
	SITE 28	3	1	VW	30 - 35	12,800	1 HP Regenerative	
	SITE 44	3	1	VW	18 - 43	6,100	1 HP Regenerative	$158,806.15

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BASE	SITE	NUMBER OF VMP'S[a]	NUMBER OF VENT WELLS	VENT WELL (VW) IDENTIFIER	VW SCREENED INTERVAL[b] (feet)	TREATMENT VOLUME[p] (Cubic Yards)	BLOWER SIZE AND TYPE	COST[d]
DAVIS-MONTHAN, AZ	SITE 35	8	4	VW1	223 - 233	271,100	2 HP Regenerative	
				VW2	163 - 183			
				VW3	105 - 120			
				VW4	60 - 80			
	SITE 36	3	1	VW	16.5 - 96.5	40,400	1 HP Regenerative	$432,007.80[n]
CANNON AFB, NM	SWMU 70	3	1	VW	10 - 110	13,500	1 HP Regenerative	$126,286.40
SHAW AFB, SC	FTA-01	4	2	VW1 & VW2	5.5 - 9.5	900	2 HP Rotary Vane	
	Site SS-15	3	1	VW	12 - 41	4,300	1 HP Regenerative	$120,025.60
FT. DRUM, NY	AREA 1595 FSA	3	1	VW	5 - 10	1,900	1 HP Regenerative	$55,914.75
MT. HOME AFB, ID	POL AREA	3	1	VW	4.2 - 18.2	1,900	1 HP Regenerative	$55,418.85
CAMP PENDLETON, CA	BLDG 13115	4	2	VW1	5.75 - 39.25	4,100	1 HP Regenerative	
				VW2	3.75 - 14			$85,151.50
USCG SUPP. CEN. KODIAK, AK	SITE 6B T191	2	1	VW	4.2 - 19.2	4,500	2 HP Regenerative	$68,996.65
POPE AFB, NC	ST-08	4	2	VW1	5.3 - 12.2	1,700	5 HP Rotary Vane	$81,916.55[o]

[a] VMP = Vapor monitoring point.

[b] Unless otherwise noted, screened interval provided is for vertical vent wells.

[c] HVW = Horizontal vent well.

[d] Value shown reflects total cost as of April 19, 1996 for work performed at each base as part of the Bioventing Initiative Project.

[e] NA = Not applicable.

[f] Initial drilling, soil sampling, and installation costs for this well not included as it was installed by another contractor.

[g] System was abandoned after Kelly AFB decided to excavate soils to make site available for reuse.

[h] Value includes costs for sites which are not shown, but for which initial planning and initial testing was performed. Bioventing systems were not installed at all sites.

[i] Cost includes over $120,000 for testing of Purus PADRE™ vapor treatment system at base service station site.

[j] Cost includes over $70,000 for testing of VR system internal combustion engine and Biocube™ system at BX service station site.

[k] This vent well has two screened intervals; the interval from 45.75 to 65.75 feet was cased off to prevent perched water intrusion (perched water was encountered 52 to 57 feet below ground surface).

[l] VMPs and/or VWs were installed at the site by other contractors. Number shown without parentheses represents number installed under Bioventing Initiative contract. Number in parentheses ( ) represents total number.

[m] Initial testing at this site performed by another contractor.

[n] Costs significantly higher for this Base due to the installation and 1-year operation of a soil vapor extraction system internal combustion engine and an autovalving system at Site 35.

[o] Value includes costs for work initially performed at a Langley AFB, VA site, where pilot testing was not completed.

[p] Treatment volume based on a radius of influence equal to the distance from the VW to the outermost VMP
In most cases the actual radius of influence was greater than could be measured.