BIOVENTING
PERFORMANCE AND COST
SUMMARY

July 1994

Air Force Center for Environmental Excellence

Brooks AFB, Texas

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUL 1994**	2. REPORT TYPE **Technical**	3. DATES COVERED **00-04-1992 to 00-07-1994**

4. TITLE AND SUBTITLE **Bioventing Performance and Cost Summary**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Air Force Center for Environmental Excellence,3300 Sidney Brooks,Brooks City Base,TX,78235-5112**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Additional Performing Organizations: Air Force Armstrong Laboratory, U.S. Environmental Protection Agency

14. ABSTRACT
In April 1992, the Air Force Center for Environmental Excellence (AFCEE), in cooperation with the Air Force Armstrong Laboratory and U.S. Environmental Protection Agency (EPA), began a major initiative to demonstrate the feasibility of using the bioventing technology at over 135 Air Force sites nationwide. This initiative had four objectives: 1) document remediation ability of bioventing, 2) use resulting data set to complete a bioventing principles and practices manual, 3) promote regulatory and public acceptance of the technology, 4) begin remediation at 135 fuel-contaminated sites at minimum cost to the taxpayer. Bioventing stimulates the natural in situ biodegradation of petroleum hydrocarbons in soil by providing oxygen to existing soil microorganisms. Between 1992 and 1994 initial bioventing tests have been completed at 137 Air Force sites and bioventing technology has been approved for application in 31 states and all 10 EPA regions. Initial test data from 137 sites has revealed that bioventing has almost universal application for remediating hydrocarbon-contaminated soils. Bioventing was found to be infeasible at only 2 of 137 sites (due to a combination of high moisture content and fine-grained soil). More soluble, mobile contaminants such at benzene, toluene, ethylbenzene and xylene are preferentially removed over contaminants such as total petroleum hydrocarbons. Case histories are also given for three sites. Based on Air Force and commercial experience, the estimated cost of bioventing ranges from $10 to $60 per cubic yard with the higher costs associated with smaller sites.

15. SUBJECT TERMS
bioventing, fuel contamination, BTEX, benzene, ethylbenzene, toluene, xylene, TPH, total petroleum hydrocarbons, soil remediation

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**13**	

PERFORMANCE AND COST SUMMARY

WHAT ARE THE OBJECTIVES OF THIS INITIATIVE?

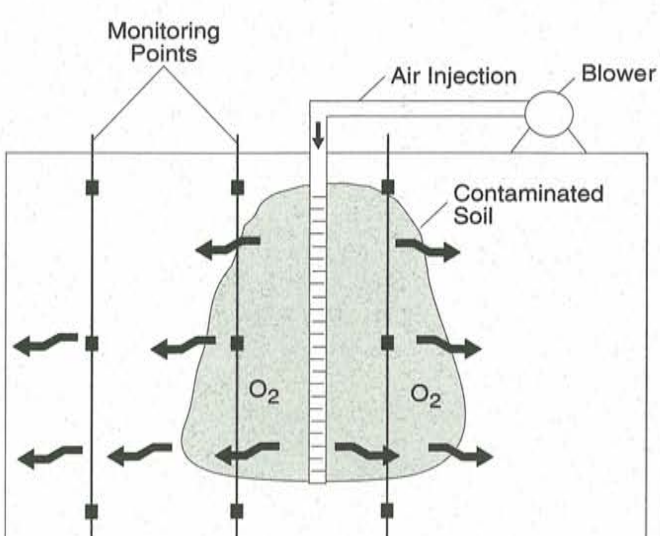
In April 1992, the Air Force Center For Environmental Excellence (AFCEE), in cooperation with the Air Force Armstrong Laboratory and U.S. Environmental Protection Agency (EPA), began a major initiative to demonstrate the feasibility of using the bioventing technology on over 135 Air Force sites nationwide. 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 remediating 135 fuel-contaminated sites at minimum cost to the taxpayer.

❖ ❖ ❖ ❖

WHAT IS BIOVENTING AND WHY WAS THIS TECHNOLOGY SELECTED?

Bioventing is a promising new 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 vacuum 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 soil contamination as illustrated below. In addition to degradation of adsorbed fuel residuals, volatile compounds also are biodegraded as vapors move slowly through biologically active soil.



Typical Bioventing System

Although this technology was first applied by the Dutch engineer J. Van Eyk (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 20 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 1500 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.

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 on sites where vapor emissions must be treated (Reisinger, 1993). The bioventing technology is mechanically simple and requires minimum maintenance, making it a cost-effective solution in an era of funding shortfalls and reduced manpower.

❖ ❖ ❖ ❖

HOW IS TESTING PERFORMED AT EACH BIOVENTING SITE?

There are six common tasks performed at each bioventing test site. Two contractors, Engineering-Science, Inc. and the Battelle Memorial Institute, have been responsible for completing these bioventing tasks.

- Each test begins with a site meeting and technology briefing to base officials and local regulatory agencies.

- A site-specific test work plan is prepared describing where and how the test will be conducted. The generic *Test Plan and Technical Protocol for Bioventing* is provided as a supplement to the work plan to more completely describe test procedures.

- A preliminary soil gas survey is conducted to locate the area of depleted soil gas oxygen concentrations and to confirm that bioventing is required. Numerous sites have been found to be naturally aerated and natural biodegradation is occurring at a satisfactory rate to achieve remediation without bioventing.

- Initial testing is completed to determine if site soils are permeable enough to allow distribution of oxygen and to estimate the rate of fuel biodegradation. Initial soil and soil gas samples are collected and analyzed and an initial test report is provided to the base. If favorable conditions exist for bioventing, a small air injection system is installed for a one-year period of air injection.

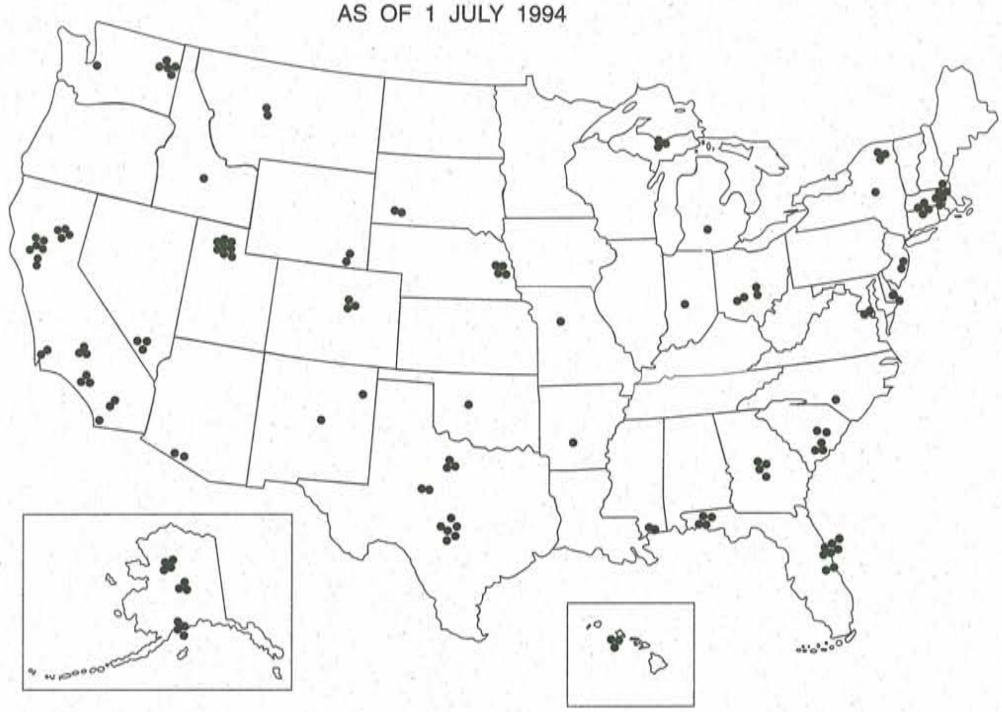
- During the one-year extended testing, *in situ* respiration rates and the radius of oxygen influence are monitored for each site. At many sites, the radius of oxygen influence from a single air injection well encompasses the entire contaminated soil volume resulting in full-scale remediation.

- At the end of 1 year of extended testing, soils and soil gas are resampled to determine bioventing progress and a letter is provided to the base recommending continued operation of the pilot-scale system, upgrade to a full-scale system, or in some cases, additional confirmatory soil samples to support site closure.

WHAT PROGRESS HAS BEEN MADE ON THIS INITIATIVE?

Between April 1992 and July 1994, initial bioventing tests have been completed at 137 Air Force sites. Figure 2 illustrates the geographic and climatic diversity of test locations. With the endorsement of the EPA, the bioventing technology has now been approved for application in 31 states and in all 10 EPA regions. These sites are under CERCLA and RCRA jurisdiction as well as regulated under special state programs.

AIR FORCE BIOVENTING INITIATIVE LOCATIONS
AS OF 1 JULY 1994



JOHNSTON ATOLL

As of 1 July 1994, extended bioventing systems are now operating at 110 sites on 48 Air Force installations. Table 1 summarizes the overall progress of the bioventing initiative. In addition to the extensive field work, AFCEE has sponsored two technology transfer conferences attended by over 400 Air Force and DOD personnel and has encouraged bioventing development in the private section through presentations at over a dozen national conferences. Initial testing at all sites is scheduled for completion before 1 September 1994.

BIOVENTING INITIATIVE STATUS

	No. of Bases	No. of Sites
Initial Site Visits	59	158
Completed Work Plans	56	147
Initial Testing Complete	51	137
One-Year Tests Underway	48	110
Awaiting Regulatory Approval	2	5
Construction in Progress	3	4
Natural Attenuation Sites	7	18
Six-Month Respiration Tests	41	81
Final Soil Sampling	21	37

TABLE 1

WHAT TYPE OF SITE IS BEST SUITED FOR BIOVENTING?

Initial test data from 137 sites has 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 is underway to determine what factors produce the highest rates of *in situ* biodegradation. While warm, moist, sandy soils are optimum for oxygen distribution and 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 which have been 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 has generally been 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 is 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 is excessive soil moisture. A combination of high moisture content and fine-grained soils has made bioventing infeasible at only two of the 137 test locations.

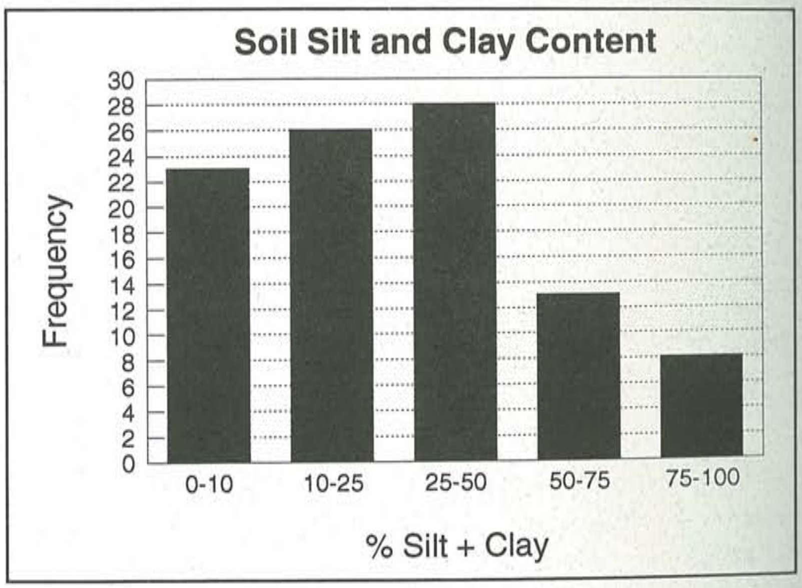


FIGURE 3

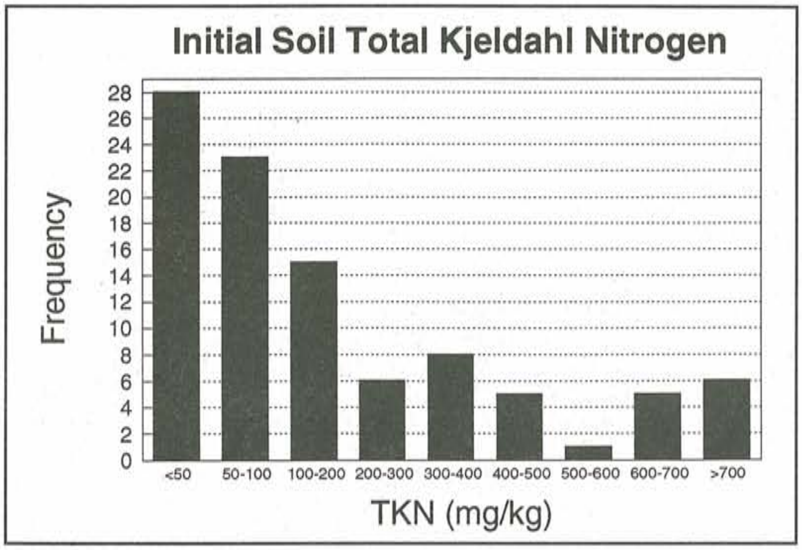
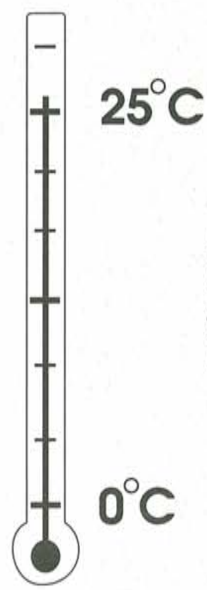


FIGURE 6

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 have been sufficient to sustain biological respiration at sites when the most limiting element, oxygen, is provided. A major question to be addressed by this test initiative, and supporting statistical analysis, is whether or not sites with high natural nutrient levels exhibit higher long-term respiration rates than low-nutrient sites.

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

A frequency chart is not provided for soil temperature; however, thermocouples have been 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, 1992a). Previous research has shown that the vanHoff-Arrhenius equation provides a good estimate of temperature effects on soil microbial activity (Miller, 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 occurs in 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 pounds of oxygen for every pound of hydrocarbon degraded, oxygen utilization can be converted into milligrams of fuel biodegraded per kilogram of soil each year. Figure 7 illustrates the wide variation in estimated fuel biodegradation rates occurring at test sites.

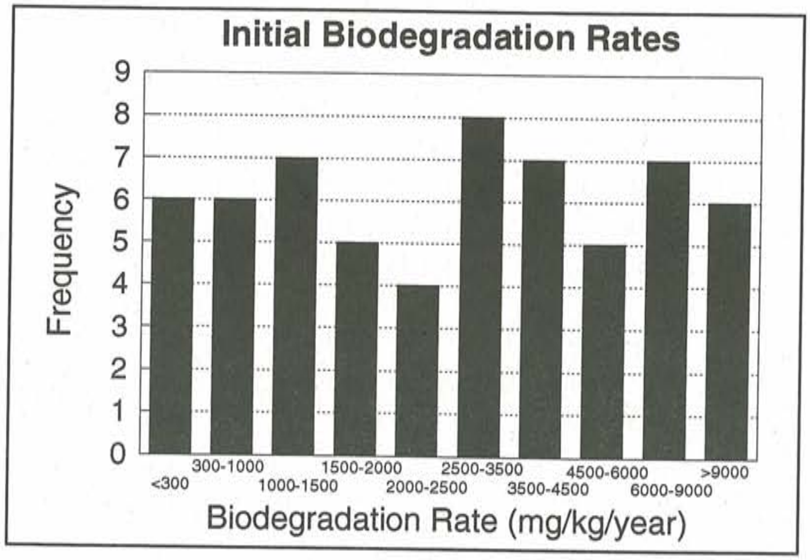


FIGURE 7

If a risk-based approach to site cleanup is used which focuses on removing the soluble, mobile, and more toxic benzene, toluene, ethylbenzene, and xylene (BTEX) constituents of fuel hydrocarbons, remediation times can be significantly reduced. Based on Tyndall AFB pilot test data presented in Figure 8, the BTEX fraction was removed preferentially compared to total recoverable petroleum hydrocarbon (TRPH) removal during this 200-day test (Miller, 1990). The ability of bioventing to preferentially remove benzene and other aromatics makes this technology well-suited for risk-based remediations.

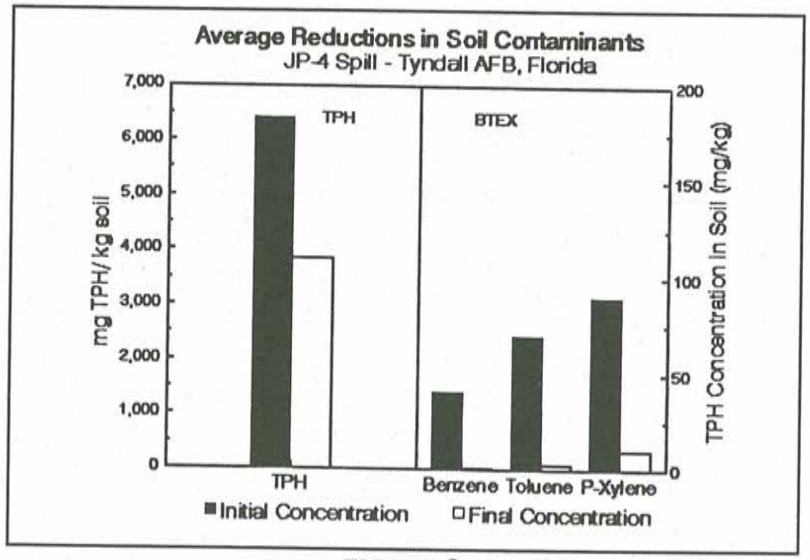


FIGURE 8

Figure 9 illustrates the average TPH and BTEX removal achieved in soils after 1 year of bioventing based on 39 samples at 16 sites. Figure 10 also illustrates the preferential reduction in soil BTEX concentrations achieved after one year of bioventing. Note the increasing frequency of low BTEX concentrations compared to TPH, which has experienced less significant reductions.

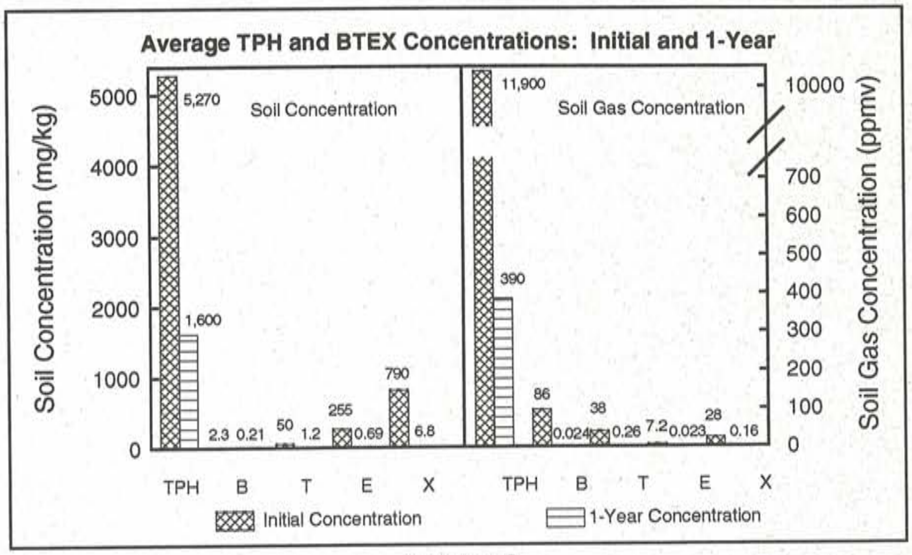


FIGURE 9

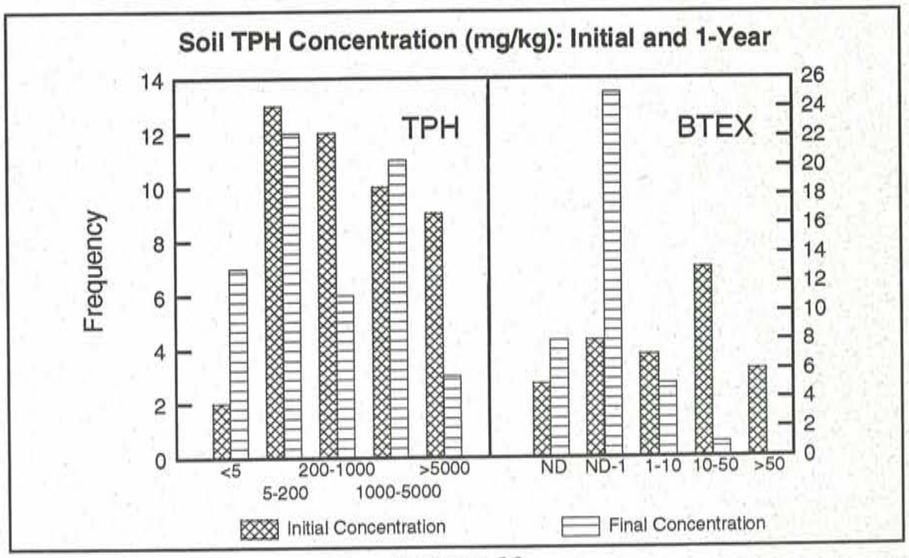


FIGURE 10

RESULTS OF FLUX MONITORING AT BIOVENTING SITES

Base	Site Type	Air Injection Rate (scfm)	Screen Depth (ft)	Total Flux Estimate (grams/day)	Initial Soil Gas TVH (ppmv)
Plattsburgh AFB, NY	Fire Training Pit	13	10-35	200	8,400
Beale AFB, CA	Fire Training Pit	30	10-25	70	4,800
Bolling AFB, D.C.	Diesel Spill	20	10-15	200	860
Fairchild AFB, WA	JP-4 Spill	15	5-10	150	29,000
McClellan AFB, CA	Diesel Spill	50	10-55	30	380

TABLE 2

Volatilization

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 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, 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 concentration at these sites is shown is Table 2. To date, the maximum surface emission that has been observed is 2.5 milligrams/day/square meter. Rates of biodegradation are typically 100 times greater than rates of volatilzation from these sites. In some situations, such as shallow gasoline contaminated soil, air injection could produce unacceptable surface emissions. At these sites, soil vapor extraction and vapor treatment may be required to reduce high soil vapor concentrations before air injection can be used.

HOW MANY SITES HAVE BEEN REMEDIATED USING BIOVENTING?

Because bioventing is a new technology, relatively few sites have operated for the time required for complete fuel biodegradation. The following case studies provide a snapshot of the progress to date at several pilot- and full-scale bioventing sites.

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 these 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 11 illustrates the 98-percent reduction in fuel contamination achieved during the 18-month demonstration. Following this demonstration, the State of Utah approved closure of this site.

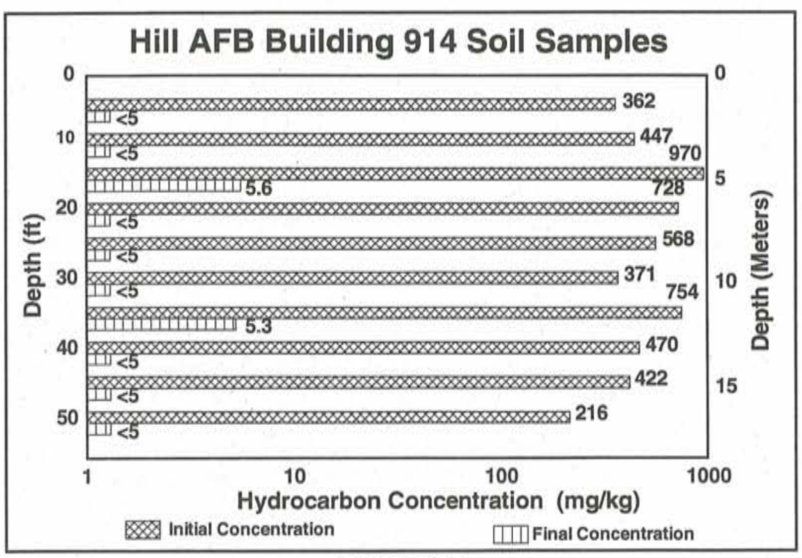


FIGURE 11

Kelly AFB, Site FC-2

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

Bioventing 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 48 standard cubic feet per minute (scfm) produced a radius of oxygen influence of at least 35 feet.

Biodegradation Rates: An average initial biodegradation rate of 5,600 milligrams of fuel per kilogram of soil per year was estimated based on test results.

Soil Remediation Achieved: Several soil and soil gas samples were collected after 1 year of bioventing treatment. Figure 12 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.

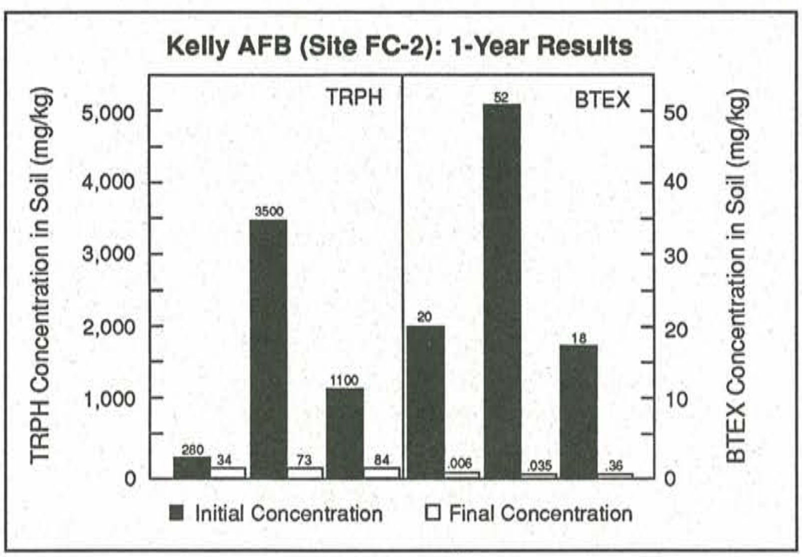


FIGURE 12

Battle Creek Air National Guard Base (ANGB) Michigan, Fire Training Area

Site Description: An estimated 74,000 gallons of JP-4 jet fuel, waste oils, and hydraulic fluids were burned during training exercises at this abandoned fire training pit. Because the pit was unlined, significant quantities of these hydrocarbons have contaminated the predominantly sandy soils down to groundwater, which occurs at a depth of 30 feet.

Bioventing System: A single air injection well and three vapor monitoring points were installed at the site in September 1992. Air was injected at a rate of 40 scfm and produced a radius of oxygen influence of over 50 feet within 2 hours. This treatment radius encompassed the entire fire training pit, and Battle Creek ANGB personnel are continuing to operate the system for full-scale remediation.

Biodegradation Rates: Initial biodegradation rates of 1,200 to 3,000 milligrams of hydrocarbon per kilogram of soil per year were estimated.

Soil Remediation Achieved: Several soil and soil gas samples were collected after 1 year of bioventing treatment. Figure 13 illustrates the removal of BTEX and TRPH achieved to date. Due to the low concentrations of BTEX remaining in these soils, they are no longer a source of groundwater contamination and site closure is now a viable option.

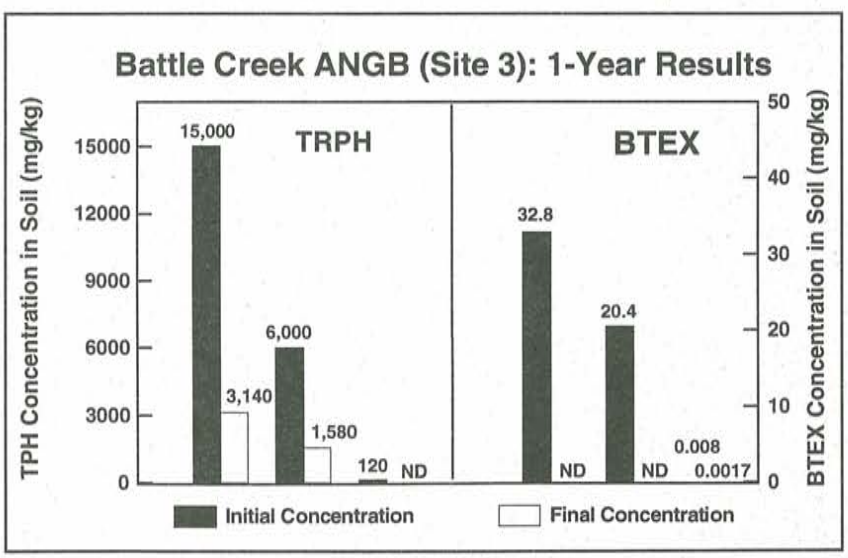


FIGURE 13

WHAT IS THE COST OF THIS TECHNOLOGY?

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 5,000 cubic yards of soil contaminated with an average concentration of 3,000 milligrams of JP-4 per kilogram of soil.

Figure 14 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 milligrams of JP-4 per kilogram of soil. Costs are provided for the following remediation scenarios: 2 years of *in situ* bioventing; 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 low-temperature thermal desorption. 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.

TYPICAL FULL-SCALE BIOVENTING COSTS

Task	Total ($)
Site Visit/Planning	5,000
Work Plan Preparation	6,000
Pilot Testing	27,000
Regulatory Approval	3,000
Full-Scale Construction	
Design	7,500
Drilling/Sampling*	15,000
Installation/Start Up	4,000
Two-Year Monitoring	6,500
Two-Year Power	2,800
Soil Sampling at Two Years	13,500
TOTAL	90,300

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

TABLE 3

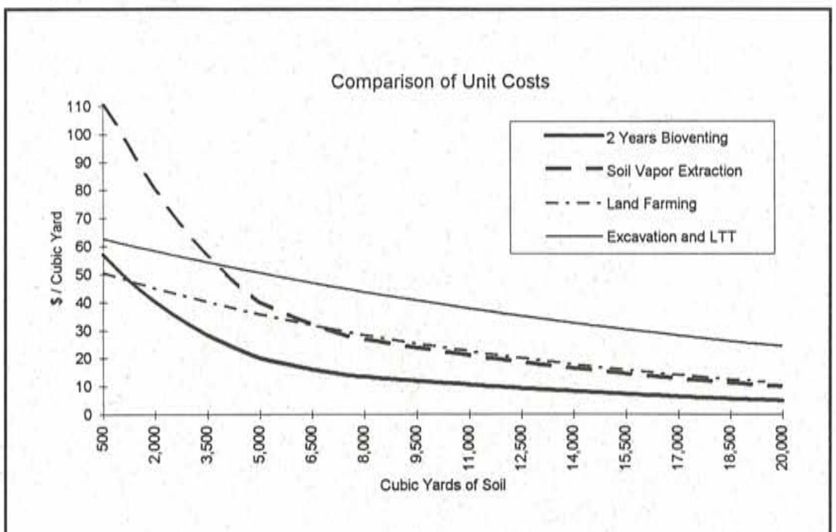


FIGURE 14

SUMMARY

The Air Force bioventing initiative is demonstrating that this technology is effective under widely varying site conditions. Initial testing has been completed at 137 sites, with 110 pilot systems now operating at 48 Air Force installations. On smaller test sites, many of these single-well pilot systems are actually providing full-scale remediation. Due to its simplicity, low cost, and minimum O&M requirements, bioventing is particularly suited for an era of reduced military manpower and funding, and for sites located on bases scheduled for closure.

Regulatory acceptance of this technology has been obtained in 31 states and in all 10 EPA regions, and the use of this technology in the private sector is growing rapidly following Air Force leadership. Bioventing will clearly 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.

❖ ❖ ❖ ❖

References

Downey, D.C., J.F. Hall, R.S. Mikdisi, D. Baskin, 1992. "Results of a Bioventing Test in Clay Soils." Published in Proceedings of Emerging Technologies for Hazardous Waste Management, ACS Special Symposium. pp 467-426. Atlanta, GA.

Dupont, R.R., W. Duecette, and R.E. Hinchee. 1991. Assessment of In Situ Bioremediation Potential and the Application of Bioventing at a Fuel-Contaminated Site. In R.E. Hinchee and R.F. Olfenbuttel, eds., In Situ and On-Site Bioreclamation, Butterworth-Heinemann, Stoneham, MA, pp. 262-282.

Hinchee, R.E., S.K. Ong, R.N. Miller, D.C. Downey, R. Frendt. 1992a. Test Plan and Technical Protocol for a Field Treatability Test for Bioventing Prepared for Air Force Center for Environmental Excellence, Brooks AFB, TX.

Hinchee, R.E. and M. F. Arthur. 1990. "Bench-scale Studies on the Soil Aeration Process for Bioremediation of Petroleum-Contaminated Soils," Journal of the Applied Biochemistry and Biotechnology, 28/29:901-906.

Miller, R.N., and Hinchee, R.E., 1990a. A Field Scale Investigation of Enhanced Petroleum Hydrocarbon Biodegradation in the Vadose Zone - Tyndall AFB FL. Proceedings NWWA/API Conference on Petroleum Hydrocarbons and Organic Chemicals in Ground Water. Houston, Texas.

Reisinger, H.J., E.F. Johnstone, and P. Hubbard. 1993. "Cost Effectiveness of and Feasibility Comparison of Bioventing vs. Conventional Soil Venting," presented at the Second International Symposium on In Situ and On-Site Bioreclamation, San Diego, CA. Publication of proceeding is pending.

Sayles, G.D., R.C. Brenner, R.E. Hinchee, C.M. Vogel and R.N. Miller. 1992. "Optimizing Bioventing in Shallow Vadose Zones and Cold Climates: Eielson AFB Bioremediation of a JP-4 Spill," Bioremediation of Hazardous Wastes, EPA/600/R-92/126.

Sayles, G.D., R.C. Brenner, R.E. Hinchee, C.M. Vogel and R.N. Miller. 1992. "Optimizing Bioventing in Deep Vadose Zones and Moderate Climates: Hill AFB Bioremediation of a JP-4 Spill," Bioremediation of Hazardous Wastes, EPA/600/R-92/126.

Van Eyk, J. and C. Vreeken. 1988. Venting-Mediated Removal of Petrol from Subsurface Soil Strata as a Result of Stimulated Evaporation and Enhanced Biodegradation. Med. Fac. Landbouww. Riiksuniv. Gent. 53:1873-1884.