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Office of Solid Waste and
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Washington, DC 20460

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Bioremediation Field Evaluation

Eielson Air Force Base, Alaska

Notice

The Bioremediation Field Initiative

In 1990, the U.S. Environmental Protection Agency (EPA) established the Bioremediation Field Initiative as part of its overall strategy to increase the use of bioremediation to treat hazardous wastes at Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA, or Superfund) and other contaminated sites. The primary purpose of the Initiative is to collect and disseminate information on the capabilities of bioremediation technologies so that EPA and state project managers, consulting engineers, and industry representatives can make better-informed decisions about applying bioremediation in the field. Participants in the Initiative include EPA's Office of Research and Development, Office of Solid Waste and Emergency Response, and regional offices, as well as other federal agencies, state agencies, industry, and universities.

The Initiative conducts a variety of activities to facilitate the exchange of information about bioremediation, including sponsoring technology-transfer conferences on topics related to bioremediation, maintaining an electronic database of information on bioremediation sites nationwide, and publishing a quarterly bulletin of recent developments in field applications of bioremediation. In addition, the Initiative provides support to states and regions for intensive evaluation of bioremediation at selected sites across the country. The extent of the Initiative's involvement at these sites varies, from providing support for laboratory feasibility studies, to assisting with field treatability studies, to overseeing and assessing full-scale site remediations.

Sites are nominated for field evaluations through the EPA regional offices or through the states with concurrence from the regional offices. To date, nine sites have been selected for performance evaluation of bioremediation: West KL Avenue Landfill Superfund site, Kalamazoo, Michigan; Libby Ground Water Superfund site, Libby, Montana; Park City Pipeline, Park City, Kansas; Bendix Corporation/Allied Automotive Superfund site, St. Joseph, Michigan; Eielson Air Force Base Superfund site, Fairbanks, Alaska; Hill Air Force Base Superfund site, Salt Lake City, Utah; Escambia Wood Preserving site-Brookhaven, Brookhaven, Mississippi; Public Service Company site, Denver, Colorado; and Reilly Tar and Chemical Corporation Superfund site, St. Louis Park, Minnesota.

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EPA also gratefully acknowledges the technical and financial contributions of those who collaborated with EPA to conduct this field evaluation. In particular, EPA wishes to acknowledge the additional funding provided by Eielson Air Force Base, the U.S. Air Force Armstrong Laboratory, and the U.S. Air Force Center for Environmental Excellence. EPA also acknowledges the assistance of Valerie Overton, Eastern Research Group, Inc. (ERG), who provided writing and editing support.

Eielson Air Force Base

ABSTRACT

This publication, one of a series presenting the findings of the Bioremediation Field Initiative's bioremediation field evaluations, provides a detailed summary of the evaluation conducted at the Eielson Air Force Base (AFB) Superfund site in Fairbanks, Alaska. At this site, the Initiative provided support for an evaluation of bioventing with soil warming systems to stimulate in situ bioremediation of soil contamination resulting from a JP-4 jet fuel spill. The purpose of the evaluation was to assess the feasibility of using bioventing technology to remediate JP-4 jet fuel contamination in a cold climate. The evaluation was conducted as a joint effort of the U.S. Air Force and the U.S. Environmental Protection Agency's (EPA's) National Risk Management Research Laboratory (NRMRL).

The Air Force and NRMRL operated a bioventing system in a contaminated site at Eielson AFB. During most of the study, the system was operated as an air injection system—one of the first such systems ever evaluated. For comparison, the system was briefly operated in the air extraction mode. Extraction bioventing was found to be much less efficient than injection bioventing.

To evaluate injection bioventing with and without soil warming, the Air Force and NRMRL operated the system in four contaminated Eielson AFB test plots: one in which the soil was warmed via circulation of heated ground water, one in which the soil was warmed via heat tape, one in which the soil was warmed via solar heating, and one with no soil warming (the control). The Air Force and NRMRL conducted a variety of tests to measure soil temperatures, microbial respiration/contaminant biodegradation rates, and extent of contaminant removal, as well as to determine whether air injection bioventing generates air emissions. All three soil warming methods raised soil temperatures and stimulated biodegradation, but the warm water and heat tape methods resulted in high soil temperatures year-round and respiration/biodegradation rates two to three times higher than the rates found in the unheated control. Significant contaminant removal occurred, and no significant air emission problems were detected.

FIELD EVALUATION

Purpose of the Evaluation

Petroleum distillate fuel hydrocarbons such as JP-4 jet fuel are generally biodegradable if indigenous microorganisms receive an adequate supply of oxygen and nutrients. Typically, much of the hydrocarbon residue at fuel-contaminated sites lies in unsaturated (vadose) zone soils immediately above the water table. To successfully bioremediate such sites, adequate oxygen must be provided to the unsaturated zone soils. To date, most efforts to bioremediate fuel spills have focused on soluble fuel components in ground water rather than hydrocarbon residues in unsaturated zone soils.

Conventional bioremediation systems use water to carry oxygen to the contamination. When water-based systems are used to remediate contaminated soil, however, oxygen usually remains the limiting factor. This problem has led researchers to investigate the use of air as an alternative source of oxygen. Air has two major advantages over water. First, on a mass basis, less air than water is needed to deliver adequate oxygen. Second, air is more diffusible than water, facilitating delivery of oxygen to soils such as clay that are relatively impermeable to water.

Researchers had reason to believe that moving air through soil could indeed supply enough oxygen to promote biodegradation of petroleum contaminants. As early as 1981, researchers had begun evaluating soil vapor extraction (SVE) technology to remediate petroleum-contaminated soils. The technology involved moving air through contaminated soils at high rates to promote volatilization of the contaminants. Although SVE technology was designed to promote volatilization, researchers found that it stimulated aerobic biodegradation as well. This finding generated interest in developing a different soil aeration technology—called bioventing—that would maximize biodegradation rather than volatilization (1-3). Researchers found that using lower air flow rates (and other design differences) accomplishes this goal (4, 5). Thus, bioventing is the process of moving air through subsurface soils to provide oxygen to microorganisms and stimulate aerobic biodegradation. As Figure 1 shows, the air movement required for bioventing can be achieved by blowing air into the soil (injection bioventing) or by creating a vacuum to pull air out of the soil (extraction bioventing).

Although both bioventing and SVE technology involve moving air through soil, they differ in design and objective: biodegradation versus volatilization.

In 1988, the U.S. Air Force initiated a study at Hill Air Force Base (AFB) to examine the potential of bioventing to remediate JP-4 jet fuel-contaminated soils. The results were promising,

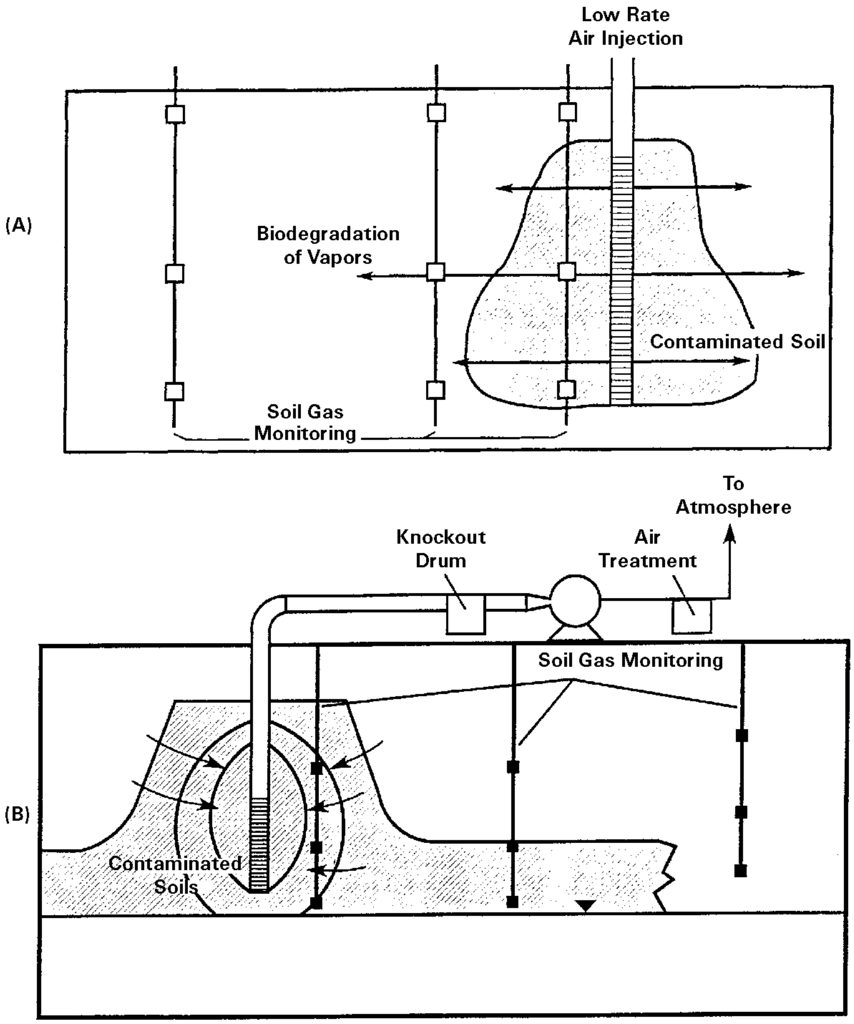

Figure 1. Schematic diagrams of injection bioventing (A) and extraction bioventing (B) technology.

prompting additional studies at Hill and Tyndall AFBs. Based on successes in these warm-weather sites, the Air Force and the U.S. Environmental Protection Agency's (EPA's) National Risk Management Research Laboratory (NRMRL) became interested in the possibility of using bioventing in cold climates. Microbial degradation occurs slowly, if at all, however, at low temperatures. The Air Force and NRMRL decided to study the use of soil warming measures to enhance the effectiveness of bio-venting in a cold climate. They selected Eielson AFB in Fairbanks, Alaska, as the study site. In winter, soil temperatures at this site drop to about 0°C.

The field evaluation at Eielson AFB was undertaken to determine whether and to what degree soil warming can enhance the effectiveness of bioventing jet fuel contaminated soil in a cold climate. The evaluation also aimed to determine whether soil warming promotes high-rate, year-round bioremediation at a lower overall cost than prolonged low-rate bioremediation at ambient temperatures. The results of the evaluation are summarized below. They have also been discussed in other publications (6-8); see those publications for additional information.

Site History

Eielson AFB is an active base located in the Alaskan interior, about 25 miles southeast of Fairbanks (see Figure 2). The base serves a wide variety of aircraft and maintains a high volume of traffic. The climate is subarctic, with an average annual temperature near 0°C. Ambient temperatures range from below -30°C in the winter to above 30°C in the summer. Permafrost is present in some areas on Eielson AFB, but not in Site 20, the area selected for this field evaluation. Site 20 is a 1-acre area of land centered over two pressurized lines that intersect the site. The pressurized fuel lines are suspected to be the source of the fuel release because the area where the lines intersect is the most highly and uni-formly contaminated part of the site.

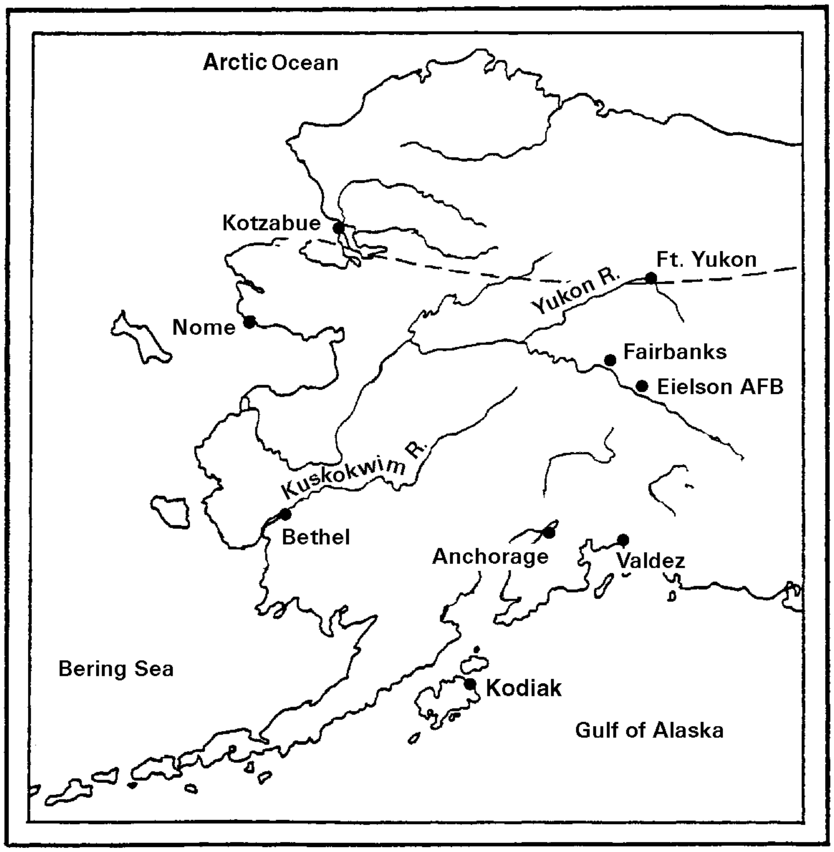

Figure 2. Location of Eielson AFB.

The Air Force conducted a site characterization in July 1991, which revealed that the surface soil at Site 20 is a mixture of sand and gravel, with silt concentration increasing to about 6 ft. The soil was contaminated with JP-4 jet fuel from a depth of roughly 2 ft to the water table at 6 to 7 ft. Total petroleum hydrocarbon (TPH) levels ranged from 100 to 3,000 mg/kg, depending on soil depth and area. A hydrocarbon sheen was visible in the ground-water monitoring wells subsequently installed, and ground-water samples showed TPH levels of 15 to 20 mg/L.

In summer 1991, the Air Force and NRMRL installed and began operating an in situ soil bioremediation system: a bioventing system consisting of an air blower plumbed to air injection/extraction (bioventing) wells. The system could operate as an injection or extraction bioventing system; the Air Force and NRMRL conducted most of the study in the injection mode, which is the generally preferred method of bioventing. Operating the bioventing system involved using the blower to inject atmospheric air into the contaminated subsurface at a rate of 25 cubic feet per minute (ft^3/min). Air injection/extraction wells were distributed uniformly at 30-ft intervals to provide relatively uniform aeration. The Air Force and NRMRL constructed four 50-ft square test plots in the contaminated area:

- A *warm water test plot* in which ground water collected via an extraction well was pumped through an electric heater, heated to about 35°C, then pumped through soaker hoses buried 2 ft underground at a rate of 1 gallon per minute (gpm). Water draining into a return manifold was returned to the extraction well for recirculation (see Figure 3). The heated water was applied below the ground surface to increase the temperature of the contaminated soil while minimizing volatilization of contaminants. Insulation was placed over the ground surface to retain heat.
- A *heat tape test plot* in which strips of heat tape were buried at a depth of 3 ft to warm the soil directly (see Figure 4). The total heating rate was about 1 watt per square foot. Insulation was placed over the ground surface to retain heat.
- A *solar test plot* in which insulation was placed over the ground surface during the winter months, then replaced with plastic mulch sheeting during the spring and summer months to capture solar heat and passively warm the soil.
- A *control test plot*, which received no soil warming.

All four test plots contained air injection/extraction wells, thermocouples for monitoring soil temperature, and three-level soil gas monitoring points for monitoring oxygen delivery and for sampling soil gas during in situ respiration tests (see Figures 5 and 6). Additional air injection/extraction wells, thermocouples, and soil gas monitoring points were installed at various points outside the test plots to permit monitoring across the contaminated site. The Air Force and NRMRL monitored natural background respiration rates

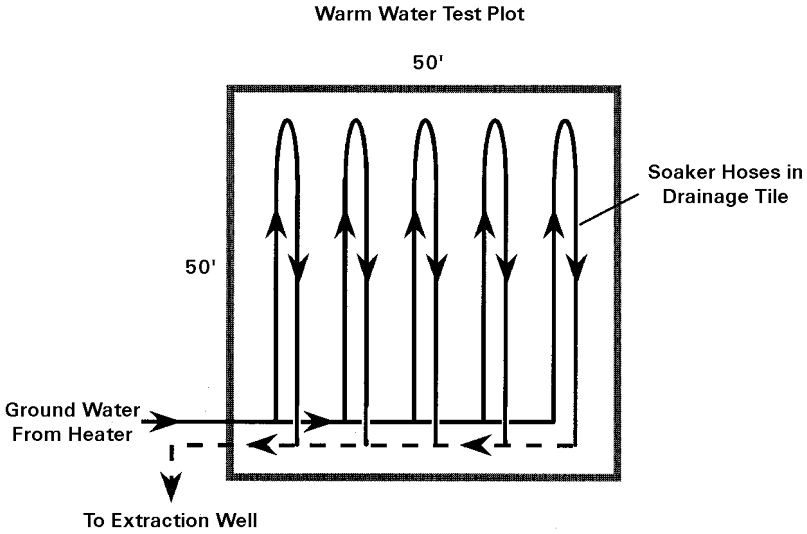

Figure 3. Circulation of heated ground water in the warm water test plot.

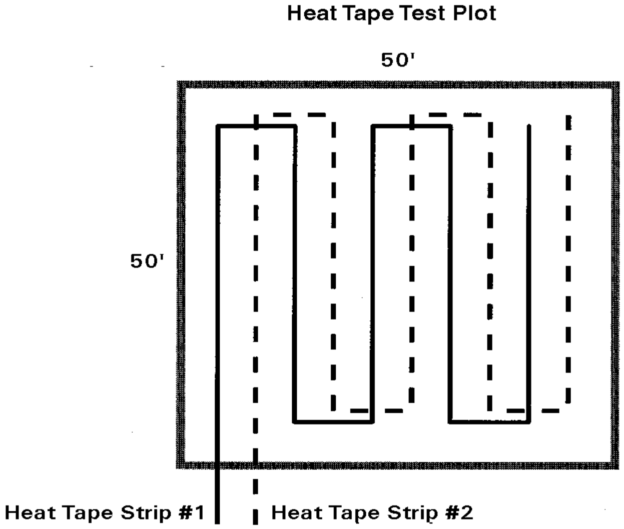

Figure 4. Arrangement of heat tape strips in the heat tape test plot.

in an uncontaminated area about 200 ft east of the contaminated site. This area received air injection (via one injection/extraction well) but no soil warming; it also contained two soil gas monitoring points and one thermocouple. Ground-water contamination was monitored via ground-water monitoring wells installed at various points in contaminated and uncontaminated areas. These tests were conducted as part of the field evaluation, discussed below.

With a couple of exceptions, the Air Force and NRMRL operated the bioventing and soil warming systems for 3 years, from summer 1991 to summer 1994. They terminated warm water circulation after 2 years in order to compare microbial activity in the warm water test plot with and without active soil warming, and they operated the heat tape test plot for only 2 years (from summer 1992 to summer 1994).

Conducting the Evaluation

The Air Force and NRMRL, with support from the Bioremediation

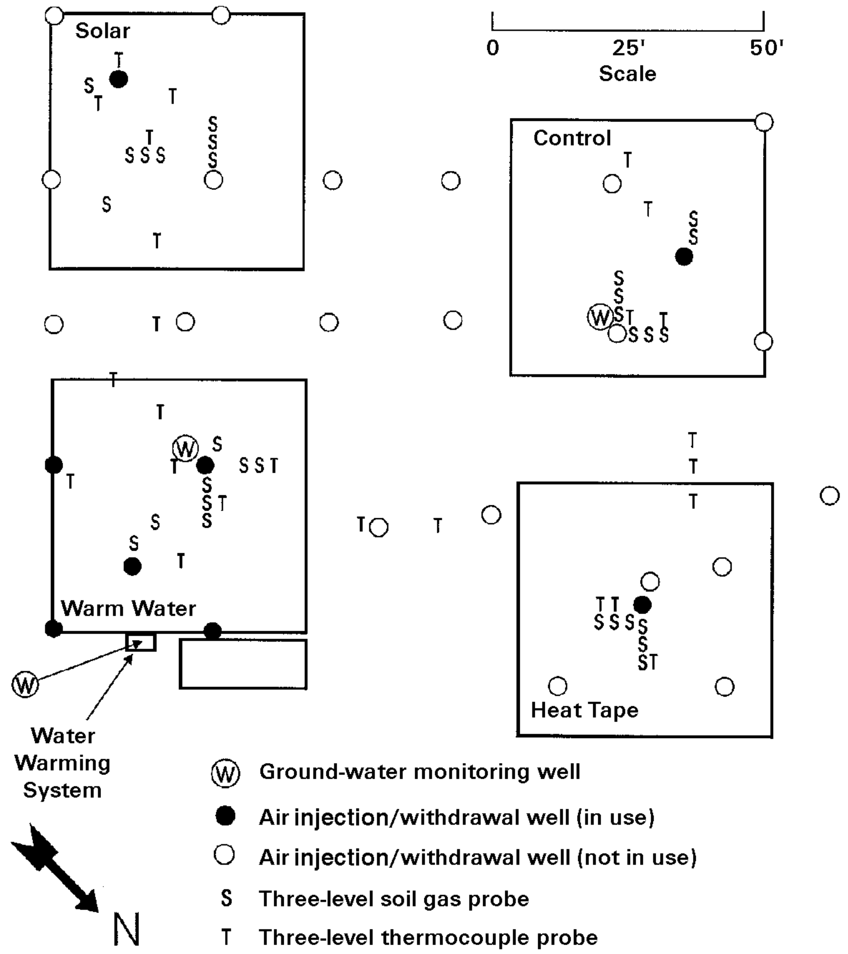

Figure 5. Schematic plan view of the bioventing site showing air injection/extraction wells, thermocouples, soil gas monitoring points, and ground-water wells inside and outside the four test plots.

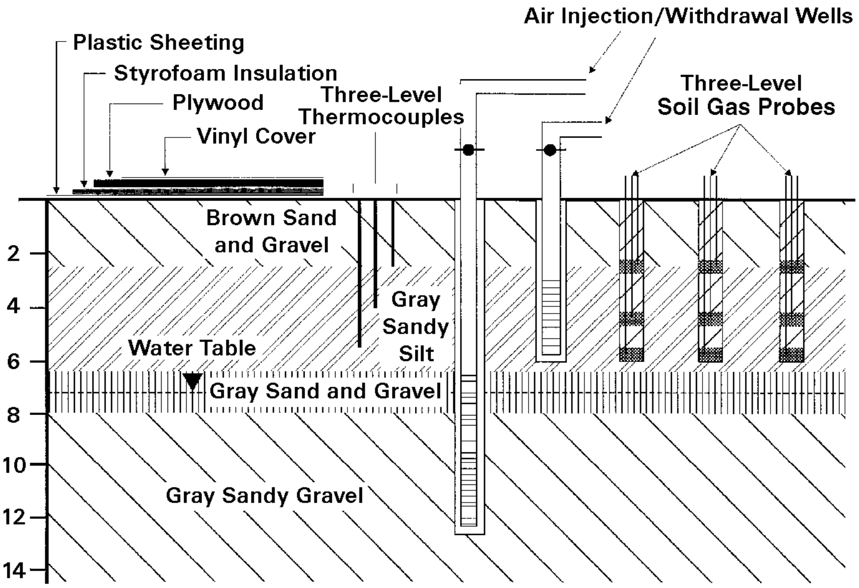

Figure 6. Cross section of a test plot showing an air injection/extraction well, a three-level thermocouple, three three-level soil gas probes, and the surface covering used in the warm water (year-round), heat tape (year-round), and solar (summer only) test plots.

Field Initiative, combined their data to perform a field evaluation of bioventing under the four test conditions: soil warming via warm water circulation, soil warming via heat tape, soil warming via solar heat, and no soil warming. The evaluation had three major elements. The first consisted of a system performance evaluation, which involved measuring the effects of the bioventing and soil warming on soil gas oxygen levels, soil temperature, microbial respiration, and contaminant levels. The second involved several other field measurements to evaluate the design and function of the bioventing and soil warming systems. The third was a cost evaluation to estimate and compare the costs of operating the systems.

System Performance

Soil Gas Sampling

To assess the effectiveness of the bioventing system in aerating the soil in the test plots, the Air Force and NRMRL conducted soil gas sampling about once a week. Prior to bioventing, oxygen levels were low (mostly less than 10 percent), and carbon dioxide and total hydrocarbon levels were correspondingly high (mostly greater than 10 percent and 5,000 parts per million, respectively). After air injection was initiated, oxygen levels increased, while carbon dioxide and total hydrocarbon levels decreased. Oxygen levels in the warm water test plot were generally lower than those in the other test plots, possibly due to the higher moisture content of the soil and the higher level of microbial activity (see discussion of in situ respiration tests below). Nevertheless, except during in situ respiration tests (see below), soil gas oxygen levels almost always exceeded 8 percent. As a result, oxygen level had no effect on the performance of the test systems.

Soil Temperature

Soil temperatures were collected two to three times a day by means of an automatic data logger. Warm water circulation and heat tape each raised soil temperatures substantially (see Figure 7). During the winter, the average soil temperature in these test plots was about 10°C—several degrees higher than in the solar and control test plots. During the third year of operation, when warm water circulation system was terminated, soil temperatures in the warm water test plot dropped steadily, falling to 2 to 3°C below that in the solar test plot. After the first season of solar warming, soil temperatures in the solar test plot were 1 to 8°C higher than those in the control test plot, depending on the season.

In Situ Respiration Tests

The Air Force and NRMRL conducted in situ respiration tests at selected soil gas monitoring points once a month, and in all soil gas monitoring points once every 3 months (9, 10). To conduct the tests, the Air Force and NRMRL monitored soil gas oxygen and carbon dioxide levels during air injection, then turned off air injection and periodically measured the oxygen and carbon dioxide levels over a period of several days. They used these measurements to calculate oxygen consumption and carbon dioxide production rates, which they in turn used to estimate biodegradation rates.

Figure 8 shows the average rate of biodegradation in each test plot during the study period. The high moisture content of the soil in the warm water test plot made soil gas sampling difficult, especially in the deeper soil gas monitoring points, where contamination levels (and thus respiration/biodegradation rates) were highest. As a result, the average biodegradation rates shown for the warm water test plot are probably underestimates. Nevertheless, during warm water circulation, biodegradation rates in the warm water test plot were higher than those in the other test plots—typically, three to four times higher than those in the solar and control test plots.

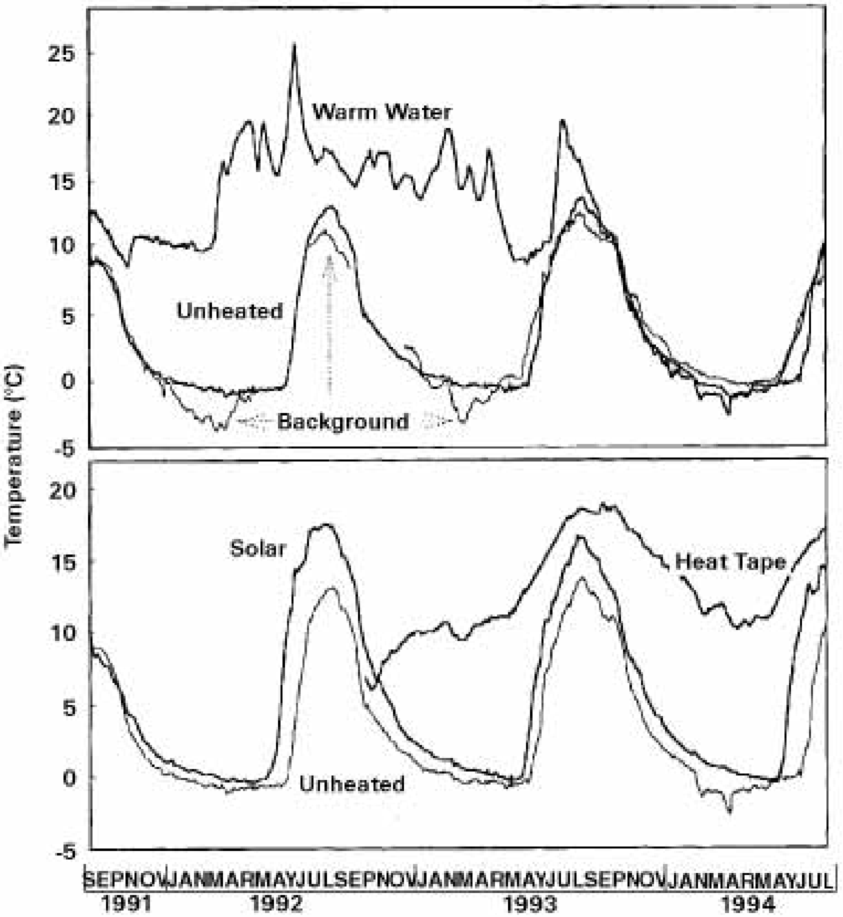

Figure 7. Average soil temperature in each of the four test plots and in the background area during the 3 years of bioventing.

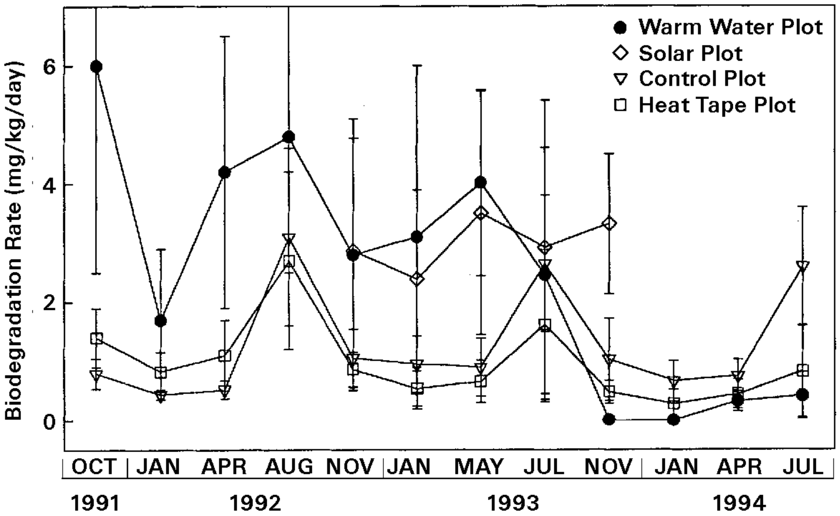

Figure 8. Average rate of biodegradation in each test plot during the 3-year study period, as measured by in situ respirometry.

During the winter of 1992 to 1993, when both were operating, the warm water and heat tape test plots showed similar biodegradation rates, although again the warm water test plot biodegradation rates are probably underestimated. After warm water circulation was terminated, biodegradation rates in the warm water test plot fell below those in the solar and control test plots. The Air Force and NRMRL speculated that the microorganisms might have adapted to higher temperatures, causing them to become inactive when exposed to lower temperatures. After the first season of solar warming, biodegradation rates in the solar test plot were slightly higher than those in the control test plot. Biodegradation rates in the heat tape test plot could not be measured in 1994 due to excess moisture in the test plot caused by high precipitation and poor drainage.

By plotting logarithm biodegradation rates in the four test plots against inverse soil temperatures in these plots, the Air Force and NRMRL determined that the biodegradation rate was temperature dependent, as expected (see Figure 9). This temperature dependence had a substantial impact on hydrocarbon removal. The total amount of hydrocarbon removed during the study period was calculated based on the average biodegradation rate per season. Total hydrocarbon removal was an order of magnitude higher in the warm water test plot than in the solar and control test plots (see Figure 10). Total hydrocarbon removal in the warm water and heat tape test plots could not be meaningfully compared because data for the first year of operation of the heat tape test plot were not available.

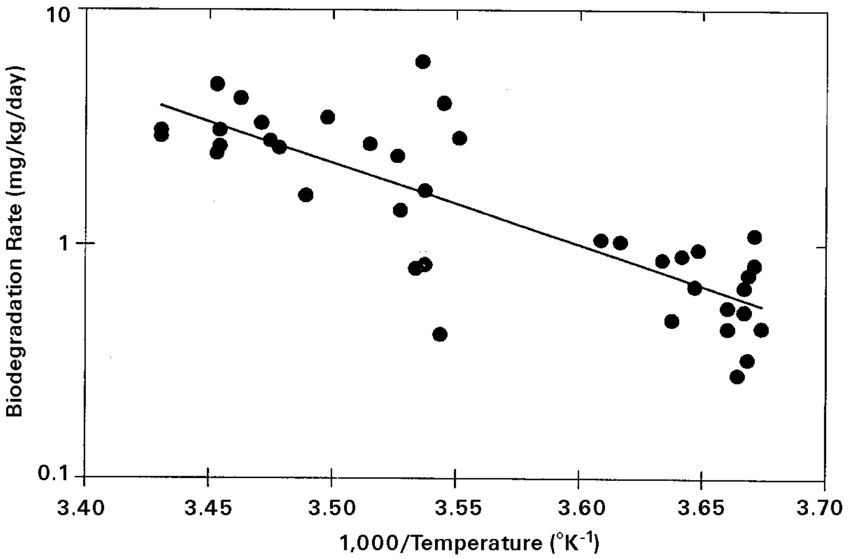

Figure 9. An Arrhenius plot of the temperature dependence of the biodegradation rates seen at Eielson AFB.

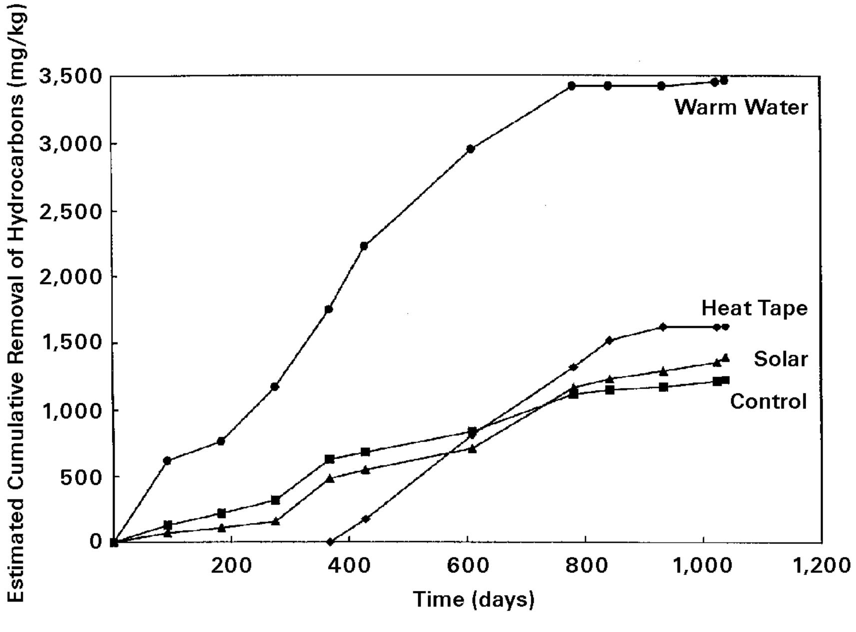

Figure 10. Calculated cumulative amount of hydrocarbons removed from each of the four test plots over the 3-year study period.

Contaminant Levels

The Air Force and NRMRL collected soil samples from the test plots and background area (1) at the beginning of the study, (2) in September 1992 (after a little over a year of operation), and (3) at the end of the study. The September 1992 sampling was conducted because the initial sampling did not include samples from the deeper depths, where much of the contamination was found. The Air Force and NRMRL collected ground-water samples from the ground-water monitoring wells in the test plots and background area at the beginning and end of the study. They analyzed the soil and ground-water samples for petroleum hydrocarbon contamination using modified standard EPA methods for gas chromatography.

Figures 11 and 12 show initial and final soil TPH and benzene, toluene, ethylbenzene, and xylene (BTEX) levels by soil depth, averaged across the four test plots. Soil TPH and BTEX levels dropped dramatically, indicating that bioventing resulted in significant contaminant removal. Similarly, average TPH and BTEX levels in ground water dropped from 6.1 mg/L to 0.65 mg/L and from 9.4 mg/L to nondetect, respectively.

Other Field Measurements

Surface Air Emissions Testing

Proposals to use bioventing for soil remediation have raised concern that contaminant volatilization might occur, resulting in transfer of soil contaminants to the atmosphere. To determine if the system used in this study resulted in significant atmospheric loading of volatile petroleum contaminants, the Air Force and NRMRL performed two types of surface air emissions tests: dynamic surface emissions sampling and helium tracing.

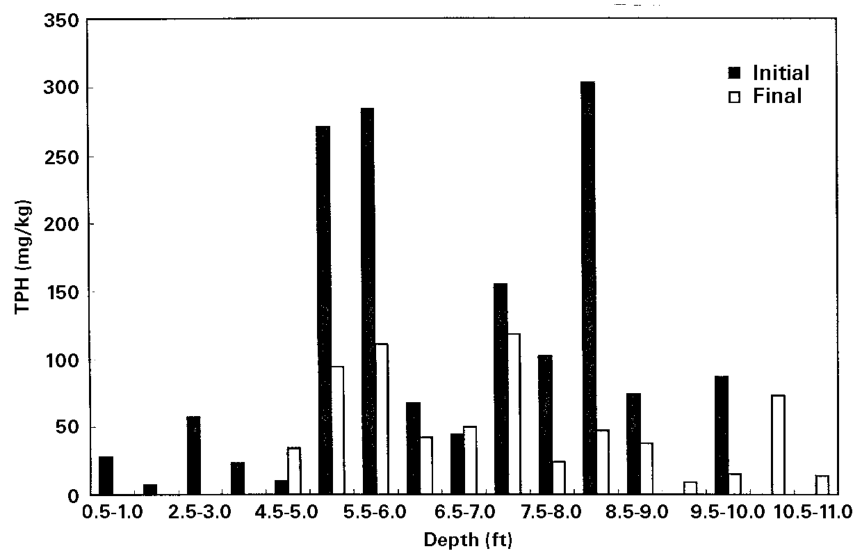

Figure 11. Average TPH concentrations in the soil across the site at the beginning and end of the bioventing study.

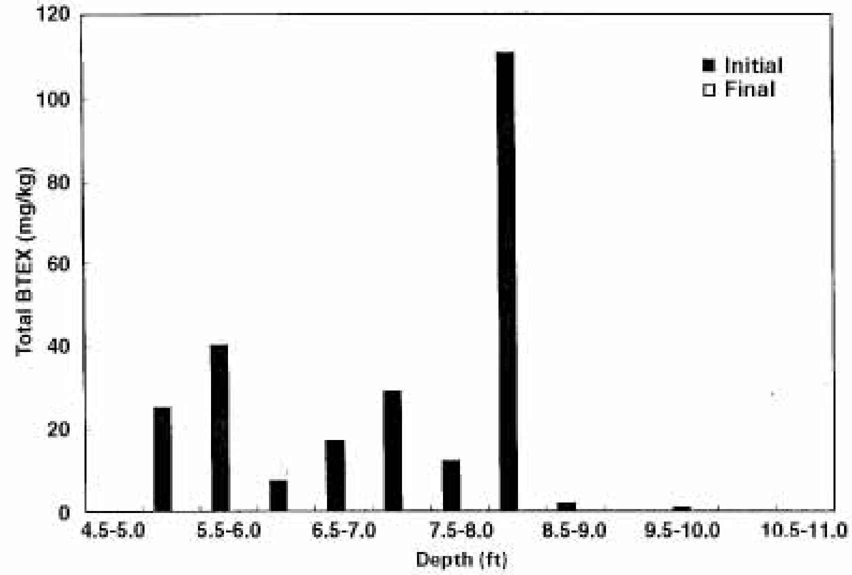

Figure 12. Average BTEX concentrations in the soil across the site at the beginning and end of the bioventing study.

The dynamic surface emissions sampling method involved enclosing an area of soil under an inert box, purging the ambient air above the soil with high-purity air to allow an equilibrium to be established between hydrocarbons emitted from the soil and the organic-free air, sampling the equilibrated air, quantifying the concentration of BTEX and TPH in this air by gas chromatography, and calculating emission rates based on the concentrations thus measured. Seven such tests were performed in 1993 and 1994; most were performed in the control and background areas, with and without air injection. The emission rates reported below represent averages based on measurements taken at several locations within a test plot. In general, emissions in the control area were higher when the bioventing system was on than when it was off. When extrapolated to assume a 1-acre test area, average benzene emission rates were 0.00083 lb/day with air injection and 0.00021 lb/day without air injection in the control area, and 0.00021 lb/day without air injection in the background area (see Table 1). Thus, bioventing did increase surface emissions, but emission levels were not much higher than background levels, and they were well below regulatory limits. Surface emissions were higher during the warm testing periods than during the cold testing periods. This seasonal variation was less pronounced in 1994 than in 1993, suggesting that soil gas hydrocarbon concentrations had diminished and therefore were less available for volatilization.

Table 1

Average Benzene and TPH Emission Rates Occurring With and Without Air Injection

Average Emission Rate	Dynamic Surface Emissions Sampling	Helium Tracing
Benzene		
Control test plot with air injection	0.00083 lb/day	—
Control test plot without air injection	0.00021 lb/day	—
Background area without air injection	0.00021 lb/day	—
TPH (in control test plot)	3.5 lb/day	1.5 lb/day

The helium tracer study involved placing plastic sheeting over the entire control test plot, pumping air from underneath the plastic (at a rate of 2.6 ft^3/min) while injecting 5.4 percent helium into the soil (at a rate of 2.5 ft^3/min) for about 8 days, and measuring the helium and TPH concentrations in the effluent air. One such study was conducted in September 1993. The TPH concentration in the effluent air was 340 ppm, which corresponds to an emission rate of about 1.5 lb/acre/day. This is similar to the average TPH emission rate (3.5 lb/acre/day) found during the same time of year using the dynamic surface emissions sampling method. The similarity of these results suggests that both techniques provide an accurate means of measuring surface emissions from bioventing.

Verification of Biodegradation

To provide another confirmation that bioventing was resulting in biodegradation of petroleum contaminants as intended, the Air Force and NRMRL analyzed the ratio of stable carbon isotopes in the carbon dioxide ($^{13}CO_2/^{12}CO_2$) in the soil gas samples collected during the study. Because the isotopic composition of carbon dioxide produced by hydrocarbon degradation differs from that of carbon dioxide produced by other processes, analyzing stable carbon isotope ratios is an effective means of determining whether biodegradation is occurring (11, 12). Such tests were performed six times during 1993 and 1994. Stable carbon isotope ratios in the contaminated areas (-18.40 to -29.16‰) were consistent with hydrocarbon degradation, while those in the uncontaminated background area (-10.12 to -19.12‰) were consistent with natural organic matter metabolism.

Soil Gas Permeability and Radius of Influence

For the purpose of this field evaluation, the Air Force and NRMRL placed air injection/extraction wells relatively close together (15 ft apart) to ensure adequate and uniform aeration of the test plots at Eielson AFB. To determine what blower size and well placement configuration would be optimal for full-scale bioventing operations, the Air Force and NRMRL measured soil gas permeability and the radius of influence of the injection/extraction wells used at the Eielson AFB site. Soil gas permeability is the soil's capacity for gas flow, while radius of influence is the greatest distance from an injection/extraction well where measurable soil gas movement (i.e., measurable vacuum or pressure) occurs.

The Air Force and NRMRL measured the pressure in the various soil gas monitoring points during air injection. The pressure values recorded at a depth of 6 ft are discussed here because that is the depth at which most of the contamination was located. Based on the pressure measurements, the Air Force and NRMRL calculated permeability values of 0.56 to 1.0 darcy (see Table 2), indicating that soil gas permeability was relatively uniform throughout Site 20 and that the soil warming systems did not significantly affect soil gas permeability. The radius of influence ranged from 40 to 77 ft, with an average of about 61 ft. Taking a conservative approach and using the smallest radius of influence measured (40 ft), placing injection/extraction wells 80 ft apart should be sufficient to achieve adequate and uniform soil aeration in full-scale bioventing operations. Nine wells would treat more than 1 acre of a contaminated site.

Tests Comparing Air Injection, Air Extraction, and Air Extraction With Reinjection

During most of the study period, the Air Force and NRMRL operated the bioventing system as an injection system. Injection bioventing is generally preferred over extraction bioventing, in part because it is less costly. Some researchers are concerned, however, that the injected air could

Table 2

Permeability of the Soil and Radius of Influence of the Injection/Extraction Well in Each Test Plot at a Depth of 6 Ft

Test Plot	Mode of Bioventing	Permeability (darcy)	Radius of Influence (ft)
Warm Water	Injection	1.0	58
Heat Tape	Injection	0.86	77
Solar	Injection	0.80	40
Control	Injection	0.56	68
Control	Extraction	0.27	36

force contaminated soil vapors to be emitted. Extraction bioventing avoids this problem because it captures contaminated soil vapor (see Figure 1). It is more costly, however, and it generates point source emissions that might require permitting and treatment. Reinjecting the off-gas might eliminate this problem but could pose problems in the winter, when moisture in the extracted gas could cause the injection/extraction lines to freeze. To compare the feasibility and efficiency of injection bioventing, extraction bioventing, and extraction bioventing with off-gas reinjection, the Air Force and NRMRL operated the bioventing system at Eielson AFB as an extraction system in August 1993, and as an extraction with reinjection system for 5 days in September 1993.

During the extraction bioventing test, the Air Force and NRMRL measured soil gas pressure and flow rate as well as oxygen and TPH concentrations in the soil gas in each test plot. From these measurements, they determined that the soil in the test plots was rapidly aerated. They also used the measurements to calculate the mass of TPH biodegraded and volatilized in each test plot. In total, the biodegradation rate was about ten times the volatilization rate during soil vapor extraction (see Table 3). Biodegradation was probably even more dominant during injection bioventing because air injection pushes vapors from contaminated to uncontaminated areas, creating an expanded bioreactor and allowing for more biodegradation.

The Air Force and NRMRL also found that the positive pressure created by air injection in the unsaturated zone resulted in depression of the water table, while the partial vacuum created by air extraction resulted in an upwelling of the water table (see Figure 13). This was important, because lowering the water table dewatered the capillary fringe, exposing more soil to air flow and allowing this highly contaminated area to be more effectively treated. Raising the water table, in contrast, saturated more contaminated soil, reducing soil exposure to air flow

Table 3

Rate of Biodegradation and Volatilization in Each Test Plot During Extraction Bioventing, as Determined by Off- Gas Composition

Test Plot	Biodegradation Rate (lb/day)	Volatilization Rate (lb/day)
Warm Water	0.078[a]	0.0028
Heat Tape	0.31	0.055
Solar	4.4	0.35
Control	1.4	0.19
Total	6.2	0.60

[a] A flow rate of 0.05 ft^3/min was estimated for this test plot.

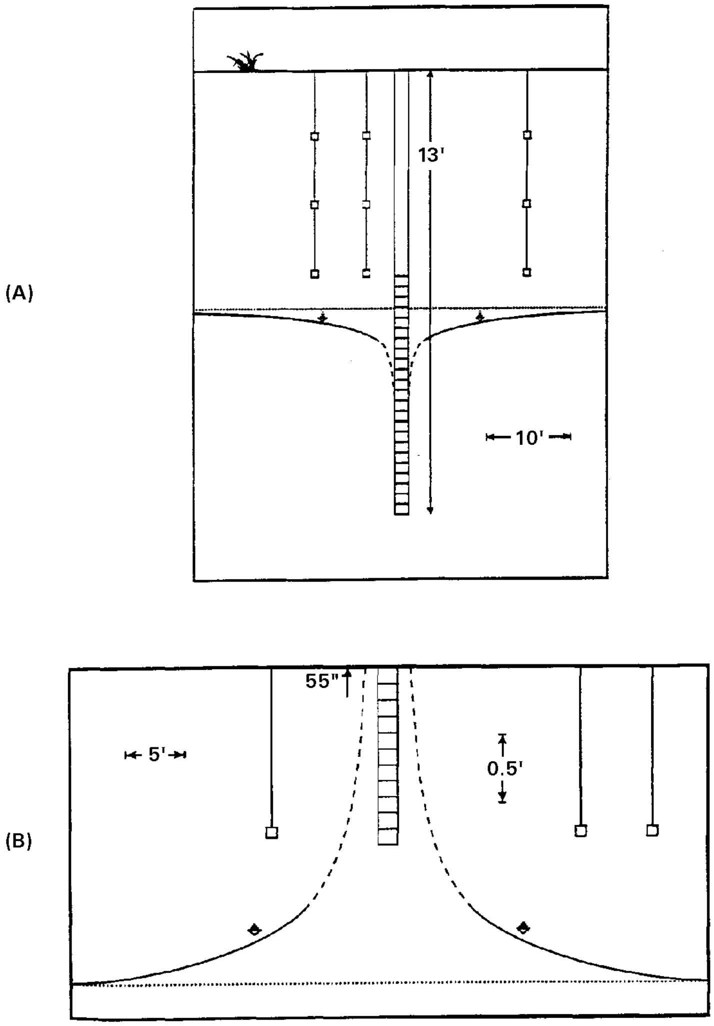

Figure 13. Depression of the water table during injection bioventing (A) and upwelling of the water table during extraction bioventing (B) at Eielson AFB. In Figure 13A, the vertical dimension is exaggerated to more clearly show the water table depression.

and reducing treatment efficiency. Not surprisingly, soil permeability and radius of influence values were much lower during extraction bioventing than during injection bioventing (see Table 2).

Unlike injection bioventing, extraction bioventing requires use of explosion-proof blowers with explosion-proof wiring, a knockout (air-water separator) to reduce the moisture content of the extracted soil gas, technologies to treat the condensate collected, insulation and/or heat tape to prevent freezing of pipes in the winter, and permitting and treatment of point source emissions. Because injection bioventing avoids these costs and affords greater treatment efficiency, the Air Force and NRMRL concluded that injection bioventing is generally preferable to extraction bioventing. They noted, however, that extraction bioventing might be preferable at contaminated sites near possible vapor receptors (e.g., basements and storm sewers) because soil extraction bioventing captures contaminated vapors that might otherwise enter these receptors.

The results of the extraction bioventing with off-gas reinjection test were generally similar to those of the extraction bioventing test. The Air Force and NRMRL noted that extraction bioventing with off-gas reinjection might be a feasible alternative to extraction bioventing alone because reinjection of the off-gas eliminates point source emissions. Extraction bioventing with reinjection, however, might increase the potential of line freezing in the winter, posing additional operational problems.

Cost Evaluation and Comparison

To evaluate the cost-effectiveness of bioventing with soil warming, the Air Force and NRMRL estimated the cost of remediating jet fuel contaminated vadose zone soils using bioventing and soil warming systems similar to those used at Eielson AFB. These estimates take into account the time needed to achieve adequate remediation based on the biodegradation rate provided by each system. They are based on optimal operating conditions rather than actual costs because the Eielson AFB systems were modified and improved during the course of the study.

The Air Force and NRMRL prepared cost estimates for two scenarios: remediation of a 5,000-yd^3 site having an average TPH contamination level of 8,000 mg/kg (see Table 4), and remediation of a 5,000-yd^3 site having an average TPH contamination level of 4,000 mg/kg (see Table 5). For a given level of contamination, the cost-per-cubic-yard of remediating soil using the four treatment systems was about the same. That is, the costs shown in Table 4 are not significantly different given the level of uncertainty associated with the estimates; similarly, the costs shown in Table 5 are not significantly different. Given the similar remediation costs, the choice of bioventing method at a site like Eielson AFB depends not on total

Table 4

Estimated Cost of Remediating Soil Containing 8,000 mg/kg TPH Using Bioventing[a]

Task	Basic	Warm Water	Solar Warming	Heat Tape
Site Visit/Planning	5,000	5,000	5,000	5,000
Work Plan Preparation	6,000	6,000	6,000	6,000
Pilot Testing	27,000	27,000	27,000	27,000
Regulatory Approval	3,000	6,000	3,000	3,000
Full-Scale Construction				
Design	7,500	7,500	7,500	7,500
Drilling/Sampling	15,000	20,000[b]	15,000	15,000
Installation/Start Up	4,000	26,000	10,500	13,000
Remediation Time Required[c]	18.8 years	5.6 years	13.8 years	6.8 years
Monitoring	61,100	19,600	48,300	22,100
Power	26,320	19,600	48,300	22,100
Final Soil Sampling	13,500	13,500	13,500	13,500
Cost per yd^3	$34.28	$30.04	$31.62	$29.82

[a] Based on the total time required to remediate a 5,000-yd^3 site.
[b] Requires installation and development of one well.
[c] Estimated based on the average biodegradation rate observed in each of the four test plots at Eielson AFB.

Table 5

Estimated Cost of Remediating Soil Containing 4,000 mg/kg TPH Using Bioventing[a]

Task	Basic	Warm Water	Solar Warming	Heat Tape
Site Visit/Planning	5,000	5,000	5,000	5,000
Work Plan Preparation	6,000	6,000	6,000	6,000
Pilot Testing	27,000	27,000	27,000	27,000
Regulatory Approval	3,000	6,000	3,000	3,000
Full-Scale Construction				
Design	7,500	7,500	7,500	7,500
Drilling/Sampling	15,000	20,000[b]	15,000	15,000
Installation/Start Up	4,000	26,000	10,500	13,000
Remediation Time Required[c]	9.4 years	2.8 years	6.9 years	3.4 years
Monitoring	30,550	9,800	24,150	11,050
Power	13,160	9,800	9,660	17,000
Final Soil Sampling	13,500	13,500	13,500	13,500
Cost per yd^3	$25.50	$26.12	$24.86	$24.21

[a] Based on the total time required to remediate a 5,000-yd^3 site.
[b] Requires installation and development of one well.
[c] Estimated based on the average biodegradation rate observed in each of the four test plots at Eielson AFB.

treatment cost but on the desired timeframe for remediation: how quickly the remediation team wishes to clean up the site versus how quickly those responsible wish to pay for the cleanup.

Actual remediation costs will also depend on site-specific factors, such as annual temperature pattern, soil gas permeability, contamination level, and so on. Regarding contamination level in particular, the Air Force and NRMRL noted that the cost of remediation using bioventing increases only somewhat with increasing levels of contamination. That is, remediating soil contaminated with TPH at 8,000 mg/kg (Table 4) does not cost twice as much as remediating soil contaminated with 4,000 mg/kg (Table 5). With or without soil warming, therefore, bioventing offers strong economies of scale.

Conclusions

With or without soil warming, bioventing stimulates biodegradation and results in contaminant removal, even in a cold climate such as that at Eielson AFB. Injection bioventing creates no significant air emission problems and is more efficient and less costly than extraction bioventing. Although bioventing alone stimulates biodegradation, adding any of the three soil warming systems tested at Eielson AFB raises soil temperatures, microbial respiration rates, and contaminant biodegradation rates. Warm water circulation raises these parameters most, followed closely by heat tape soil warming and more distantly by solar heating. The closeness of the results achieved with warm water circulation and heat tape might be misleading, since soil moisture problems associated with warm water circulation make sampling at deep monitoring points difficult. Because contamination levels and respiration/biodegradation rates are highest at these points, warm water circulation might produce even better results than those reported here. Nevertheless, heat tape might be the most efficient means of soil warming because it enhances biodegradation without causing the moisture problems associated with warm water circulation.

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