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RESULTS OF A FULL SCALE BIOVENTING TEST IN CLAY SOILS

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ABSTRACT

A long-term leak from a No. 2 diesel fuel tank resulted in the contamination of approximately 10,000 cubic yards of soil beneath, and adjacent to, an office building on a U.S. Air Force installation. Soils had been contaminated to a depth of over 40 feet, with fuel residuals ranging from approximately 500 to 2,000 mg TPH/kg. The primary regulatory concern at this site is the potential for groundwater contamination from alkylbenzenes and polyaromatic hydrocarbons. An *in situ* bioventing technique that removes fuel residuals through the introduction of oxygen (air) to the subsurface to promote microbial fuel degradation was selected for full-scale testing on the site. A primary vapor extraction well (VEW-1) was constructed near the center of the spill site in the backfill material and connected to a 50 scfm vacuum system. A secondary vapor extraction well (VEW-2) was installed in the undisturbed soils to estimate soil gas permeability. Nine multi-depth vapor monitoring points (VMPs) were used to analyze soil gas permeability, radius of influence, oxygen enhancement, and the biological respiration of fuel hydrocarbons. Three primary tests were conducted. The first test measured the vacuum influence at varying depths and distances from the central extraction well. The results clearly demonstrated the ability of this low-rate vacuum to stimulate soil vapor flow at the 35 to 40-foot depth and up to 100 feet laterally from the central extraction well. A second test studied the ability of soil gas extraction to produce an influx of oxygen-rich air from surrounding soils and the surface into the contaminated soil volume. After only 30 hours of venting, oxygen levels were increased from near anaerobic conditions at all depths and distances from the extraction well to an aerobic environment for fuel biodegradation. The final test measured the utilization of oxygen by existing soil bacteria once this additional oxygen had been supplied. For this site, an average fuel biodegradation rate of 850 mg of fuel per kilogram of soil per year was calculated. This rate of *in situ* biodegradation is in agreement with field testing conducted by other researchers who have measured biodegradation rates at 300 to 7,000 mg fuel per kilogram of soil per year. Based on the full-scale pilot test results, a bioventing remediation system was installed at the site. The results of other bioventing tests in low-permeability soils are also discussed.

INTRODUCTION

Fuel contamination in soils with total petroleum hydrocarbon (TPH) concentrations greater than 100 milligrams per kilogram (mg/kg) are considered to present a potential long-term source of groundwater contamination in California, and must be remediated to assure successful site cleanup. Because fuel-contaminated soil is not a listed RCRA hazardous waste, and is generally not ignitable, excavation and disposing of these soils in approved landfills has frequently been the most expedient remediation option. Increased costs and restrictions on land disposal, and the risk of becoming a potentially responsible party for future landfill remediation have made this option much less attractive.

A variety of soil remediation options are available for fuel-contaminated soils. Many sites with shallow soil contamination are remediated by excavating soils and treating them above ground using thermal, chemical/physical, or biological processes. Low-temperature thermal desorption processes have proven effective at rapidly removing fuels and chlorinated solvents from sand, silt, and clay soils. TPH removal rates of over 99 percent have been achieved at treatment costs of \$100 - \$150 per cubic yard given sufficient volume. In some states, fuel-contaminated soil can be used as base material for asphalt production. The costs of excavation, transportation, and processing for asphalt production can be \$35 to \$50 per cubic yard given sufficient volume. However, this option is not appropriate for the case study soils both because asphalt cannot be produced from fine grained soils and because the California regulatory agencies do not generally permit contaminated soil to be used as asphalt base.

Excavation is difficult if not impossible when contaminated soils lie beneath buildings or critical transportation corridors, or simply beyond the depth of safe and economical soil removal. Under these conditions *in situ* remediation methods may be the only viable alternative. At the case study site location, significant diesel fuel contamination migrated beneath an adjacent building, underground utilities and roadway, preventing the complete removal of all contaminated soil for above ground treatment.

Technologies for *in situ* soil remediation include soil washing, thermal methods such as vitrification and steam stripping, soil venting, and enhanced biodegradation. **Enhanced biodegradation through bioventing was selected for testing at this site due to the heavier hydrocarbon range of the contaminants and site constraints.**

The use of air as a medium to remove volatile hydrocarbons has been extensively used in soil vapor extraction systems. Due to the tremendous viscosity advantages of air, soil vapor extraction has been more successful than water flushing in contacting fuel residuals trapped in soil micropores. Air is also 1,000 times more efficient than water at transferring oxygen to unsaturated soils. Recent full-scale field tests using *in situ* soil venting to supply oxygen to the subsurface and stimulate aerobic biodegradation of fuel residuals have proven the effectiveness of the method. A full-scale soil venting project was recently completed to remediate a 27,000-gallon jet fuel spill at Hill Air Force Base (AFB) in Utah. During this 18 month project, jet fuel residuals were reduced from an average TPH concentration of approximately 900 mg/kg to less than 10 mg/kg. Monitoring of vented soil gas indicated that volatilization accounted for 60 percent of the removal, and biodegradation accounted for the remaining 40 percent (Hinchee and Miller 1991). A bioventing pilot test recently completed by Engineering-Science, Inc. at a diesel fuel contaminated site confirmed the ability of deep soil venting (>60 feet) to supply oxygen to indigenous bacteria and to stimulate diesel fuel degradation (Downey and Guest 1992).

Lack of oxygen generally limits the natural biodegradation of hydrocarbons by soil bacteria. Once oxygen is supplied by soil venting, natural bacteria multiply and thrive, using fuel hydrocarbons as their primary carbon source. **Another factor influencing fuel biodegradation is the availability of basic nutrients such as nitrogen and phosphorous.** Recent research at a bioventing demonstration at Tyndall AFB in Florida indicates that soils bacteria are able to recycle essential nutrients, and may also rely on nitrogenase bacteria to fix atmospheric nitrogen and introduce useful forms of nitrogen for fuel-degrading microbes (Miller and Hinchee 1990). Nutrients that were added to the subsurface at the Hill AFB and Tyndall AFB sites produced little or no increase in biological activity over that at control sites where nutrients were added. Biodegradation accounted for over 50 percent of the fuel removed from soils at the Tyndall AFB bioventing demonstration.

Adequate soil moisture must be available to sustain microbial populations. A column test using soils from the Hill AFB site showed increasing fuel biodegradation as soil moisture was increased from 6 to 18 percent (by weight). However, at higher moisture levels, a reduction in air permeability can limit the oxygen supply.

Because heating fuel is less volatile than jet fuel and contains a larger fraction of C_{10} and heavier hydrocarbons, biodegradation plays a larger role relative to volatilization in the removal of hydrocarbon contamination at diesel contaminated sites. Polynuclear aromatic hydrocarbon (PAH) compounds found in heating fuels are also more difficult to biodegrade than straight-chain hydrocarbons, although success in PAH biodegradation has been reported by several investigators (Lee 1988 and Srivastava 1989). Full-scale remediation may require several years at heating oil spill sites, however, the cost of remediation should be low given the simplicity and minimal operating cost of a bioventing system.

SITE CHARACTERIZATION

Site History

The 600 gallon capacity heating oil underground storage tank (UST) A20 was adjacent to Building 2171, and was used to heat the building. According to UST inventory records, the installation date of the tank is unknown but its presence on 1966 base maps indicates it was installed before that date. The removal of this UST was part of a 22 UST removal project conducted by Engineering-Science, Inc. (ES). The UST A20 was in poor condition with small holes (about 1 mm in diameter) suggesting that leakage of fuel had occurred over an extended period of time. Removal of contaminated soil, beyond the reach of the excavators (depths greater than 20 feet bgs), required a ramp on the north side of the excavation. Removal of contaminated soil was hampered by Building 2171 to the east and the presence of a gas main to the west, a gas service pipe to the north, a water main to the north, and two telephone cables to the east and south. Soil samples were collected to document the residual contamination prior to backfilling and showed residual TPA as diesel (TPHd) contamination ranged from 350 mg/kg to 2,100 mg/kg. The configuration of the tank and excavation and location of soil samples and soil sample results from the excavation are shown on Figure 1.

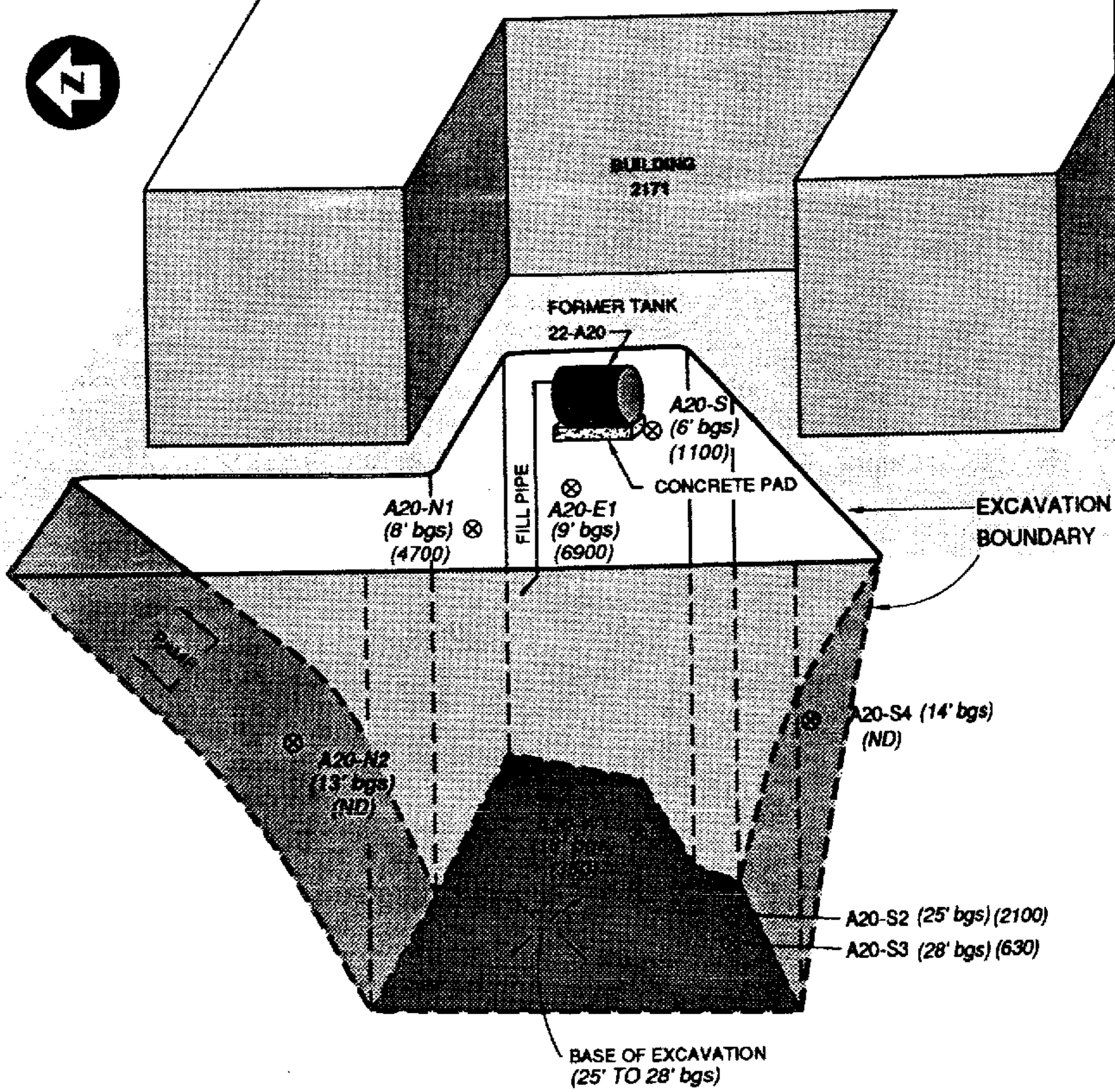
Engineering-Science, Inc., was retained to complete remediation of the contaminated soil and recommended using *in situ* bioventing to enhance the long term biodegradation of fuel hydrocarbons should the pilot test prove bioventing technology was feasible.

Soil Conditions

The pilot test was performed near the center of the site **in the backfill area** from where the most contaminated soils (ranging from approximately 4,000 mg/kg to 8,000 mg/kg) were excavated. Two vapor extraction wells (VEWs) and ten monitoring vapor monitoring points (VMPs) were installed for the test. **The principal vapor extraction (VEW-1) was installed approximately 20 feet north of the underground tank location (Figure 2).** Soil physical and chemical conditions were evaluated before implementing the test. Analyses to document baseline conditions and determine soil characteristics included aromatic volatile organic compounds, total lead, total organic carbon (TOC), selected analyses for nutrients, physical properties of the soil and soil gas. Soil samples were collected from a number of depths including the depth that corresponded to the screened interval of the VMPs. The VMPs were screened in two zones; a shallow zone between 14 and 19.5 feet and a deeper zone between 38 and 40 feet.

Figure 2 is a perspective view of the residual TPH-diesel contamination at the site recorded during the VEW and VMP installations. Analytical results are plotted adjacent to the corresponding VMP sampling interval. Samples obtained in the VMPs to the west of the sidewalk (VMPs-7, 8, and 9) had nondetectable levels of TPH-diesel. Samples collected from beneath the excavation (VMPs-5 and 6) were generally nondetect for TPH-diesel with a single sample immediately beneath the excavation at a depth of 30 feet below ground surface (bgs) having a TPH-diesel concentration of 45 mg/kg. VMP-1 located east of Building 2171 and the background VMP-10 (approximately 200 feet to the west) also had nondetectable levels of TPH-diesel. The significant residual TPH-diesel contamination appears to be limited primarily to beneath and immediately adjacent to Building 2171. TPH-diesel concentrations in the VMPs adjacent to the building (VMPs-2, 3, and 4) ranged from not detected to 1,200 mg/kg. The highest TPH-diesel concentrations recorded were 20 to 30 feet bgs. This region is highlighted on the figure. Based on samples from these VMPs, TPH-diesel soil contamination probably extends

FIGURE 1



EXPLANATION

A21 ⊗	SAMPLE LOCATION	(ND)	TPH-DIESEL (Not Detected)
(25' bgs)	DEPTH IN FEET BELOW GROUND SURFACE (bgs)	— — —	BOTTOM OF EXCAVATION ALONG EAST WALL
(630)	TPH-DIESEL CONCENTRATION (mg/Kg)		

NOTE: SAMPLE A20-W1 LOCATED ON WEST WALL

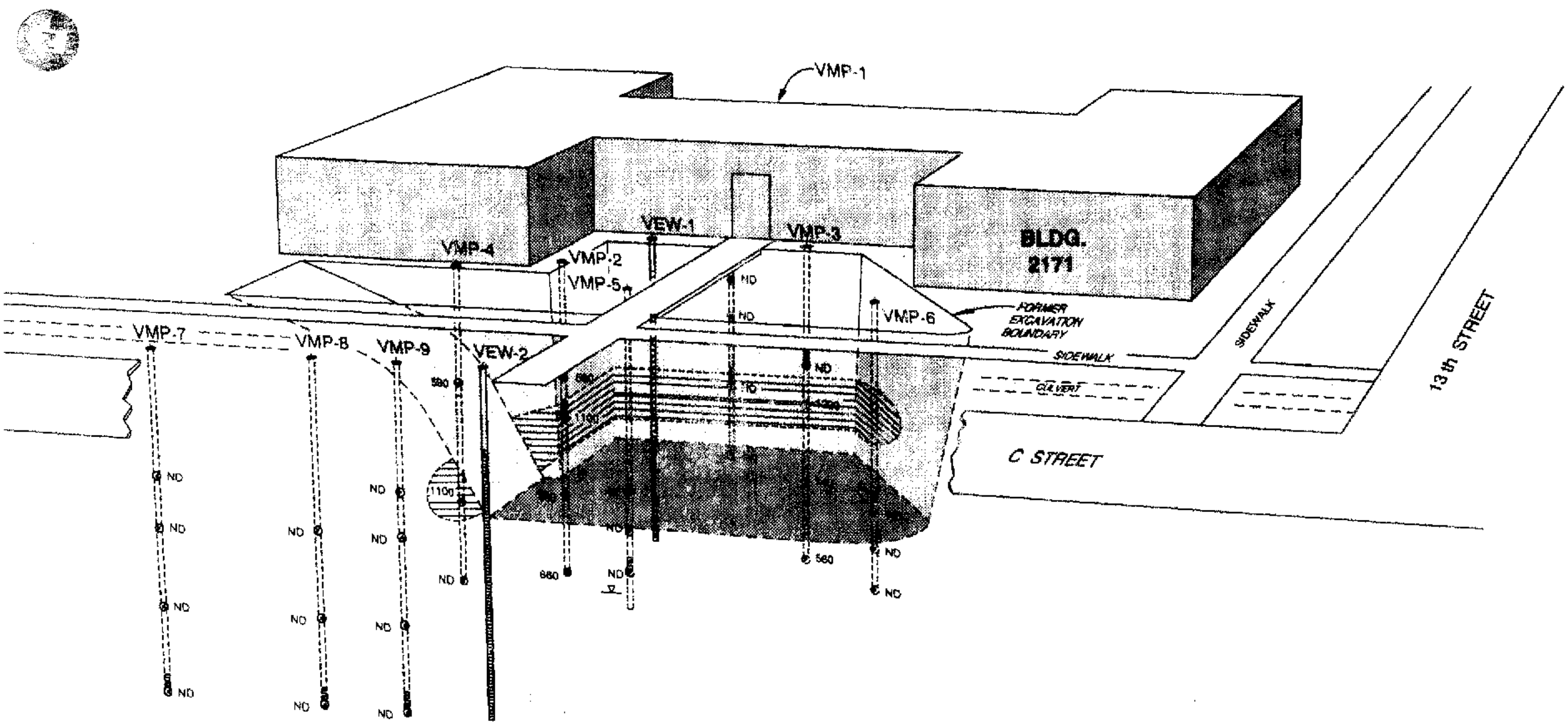
1" = 10' VERTICAL SCALE

0 5 10

0 10 20

1" = 20' HORIZONTAL SCALE

UNDERGROUND STORAGE TANK 22-A20
PERSPECTIVE VIEW
EXCAVATION ANALYTICAL RESULTS



EXPLANATION

VEW	VAPOR EXTRACTION WELL	WELL SCREEN LOCATION	
VMP	VAPOR MONITORING POINT	150 SOIL SAMPLE LOCATION SHOWING TPH-DIESEL CONCENTRATION IN mg / kg	ND NOT DETECTED
		TPH-DIESEL CONCENTRATION > 1000 mg / kg	▽ WATER LEVEL

0 5 10 APPROXIMATE SCALE IN FEET X AXIS

0 5 10 APPROXIMATE SCALE IN FEET Y AXIS

0 5 10 APPROXIMATE SCALE IN FEET VERTICAL

UST SITE A20
PERSPECTIVE VIEW AND VMP/VEW
SOIL SAMPLE ANALYTICAL RESULTS

to the groundwater table (approximately 40-45 feet bgs) near the former UST location adjacent to the building. TPH-diesel concentrations were 660 mg/kg and 560 mg/kg at a depth of 40 feet in VMP-2 and VMP-3 respectively.

The background well VMP-10 contained 100 mg/kg total organic carbon (TOC) at 14 feet bgs. The low TOC concentration (0.01 weight-percent) indicated nonfuel carbon should not significantly add to biological oxygen consumption during the respiration test.

Nutrient analyses were performed on soil samples collected from VMP-2 and VMP-3 in the shallow zone (14 to 19.5 feet bgs) and VMP-8 and VMP-9 for the deeper zone. Combined ammonia, phosphorous and nitrate-nitrite levels ranged from 121.6 mg/kg to 161.2 mg/kg in the shallow zone and between non detect (0.1 mg/kg) and 64.3 in the deeper zone. The total Kjeldahl nitrogen (TKN) concentrations were detected in the upper zone at a maximum concentration of 77 mg/kg and not detected (< 25 mg/kg) in the lower zone samples.

Soil moisture content was between 20.6 and 23.4 percent in the upper soils and 26.6 and 29.2 percent in the deeper soils. These levels of moisture are adequate to sustain microbial populations.

The surface soils at Site 22-A20 are Redding-Corning gravelly loam. Based on observations made during the removal of the A-20 UST**, the upper 28 feet of soil consists of interbedded layers of low-permeability, fine-grained silts and clays with minor lenses of sandy material.** The soils encountered during installation of the VMPs and VEWs consisted primarily of silty clays (CL) and clayey silts (ML) with interbedded thin layers of clay (CH) and fine sand (SM) to a depth of 40 feet. **Grain size analyses classified sites soils as approximately 70 percent clay/silt and 30 percent fine sand.**

Groundwater Conditions

Groundwater is confined or semi-confined at the 22-A20 site. When VMP-9 was being drilled, water was initially encountered at a depth of approximately 45 feet bgs and immediately rose in the well to a depth of approximately 40 feet bgs. Static water levels in two groundwater monitoring wells, one in the excavation and one approximately 100 feet to the west, were measured at approximately 42 feet bgs in November 1991. Groundwater flow direction is to the southwest.

TEST SITE LAYOUT

Due to the large excavation area and backfill, separate tests were conducted using two different VEWs. VEW-2 and VMPs-7, 8, and 9 were used to estimate soil gas permeability in undisturbed soils (Figure 2). VEW 1 and the remaining VMPs were used to measure vacuum response, oxygen influx and *in situ* respiration rates in contaminated soils beside and beneath the office building. This paper will focus on the results obtained using VEW-1 to enhance oxygen supply to fuel contaminated soils adjacent to and beneath the building and the rates of *in situ* biodegradation observed under oxygen-enhanced conditions.

The total depth of the VEW 1 was selected to correspond with the top of the capillary fringe, which occurs approximately 40 feet below ground surface. VEW-1 was constructed of 4-inch diameter, schedule-40, threaded and coupled polyvinyl chloride (PVC) casing and factory-slotted PVC screen. The screened interval of the vent well was set from 5 to 40 feet below the surface. The well annulus was packed with silica sand from the bottom of the screen to approximately 5 feet below ground surface. A bentonite/cement grout mixture was used to seal the remaining annular space to the ground surface.

A radial pattern of VMPs was used to allow the directional characteristics of soil permeability and oxygen influx to be determined. The VMPs were spaced at horizontal distances of 20, 35, 40, 45, and 50 feet from the extraction well. A single, 2-foot screened interval was installed in each VMP at a depth of either 14, 19, 31 or 38 feet below ground surface to allow the vacuum influence and oxygen and carbon dioxide to be measured throughout the contaminated interval. The VMPs were constructed of 2-inch diameter, schedule-40, threaded-and-coupled PVC and 2-foot sections of 0.020-inch factory-slotted PVC screen.

BIOVENTING TEST RESULTS

Initial Conditions

Prior to initiating any soil ventilation at this site, oxygen and carbon dioxide concentrations were measured at each VMP. Table 1 provides initial soil gas oxygen and carbon dioxide concentrations at each VMP screened interval. Photoionization detector (PID) readings collected during drilling and laboratory analysis of soil TPH concentrations and soil gas volatile organics at the same screened interval are also shown in Table 1. **The depletion of oxygen is most apparent near the center of the contaminated soil volume** (VMPs-2, 3, and 5) **which indicates that diesel fuel has provided the primary carbon source of aerobic bacteria.** Although soils at the screened intervals of VMP-3 and VMP-5 were not contaminated, these VMPs were located in close proximity to contaminated soils and reflect the low oxygen levels that exist in the contaminated soil volume.

Concentrations of carbon dioxide in the range of 4 to 8 percent were observed in all VMPs within the contaminated area indicating an accumulation of this primary respiration by-product in the soil gas. In many contaminated soils, initial carbon dioxide levels can exceed 15 percent (Hinchee and Arthur 1990). Lower carbon dioxide accumulations in these soils are possibly due to soil alkalinity which acts as a buffer and reacts with carbon dioxide. Carbon dioxide levels of only 1.8 percent were measured in the uncontaminated background VMP-10.

Oxygen Influence

Table 2 illustrates the effect of 30 hours of soil ventilation from VEW-1 on soil gas oxygen concentrations. The ability of vacuum extraction from VEW-1 to promote oxygen flow through the entire contaminated soil volume was clearly demonstrated by the test. Oxygen levels in the most contaminated soil volume (VMPs-2, 3, and 4) increased by an average of 12 percent. Oxygen levels in VMP-5 (38-foot depth) increased by 4 percent which indicates that the vapor extraction system will also provide an aerobic environment for fuel residuals located in the capillary fringe. Oxygen levels in an uncontaminated background well (VMP-10) remained constant at 16 percent throughout the test.

Radius of Influence of Vapor Extraction Wells

The radius of influence of a VEW is the horizontal distance from the well to the point at which a vacuum response can no longer be measured. To determine the radius of influence of VEW-2 and VEW-1, distance-vacuum graphs were constructed for VEW-2 (Test 2) and VEW-1 (Test 3) using data collected from the VMPs (Figure 3).

The distance-vacuum graphs presented on Figure 3 indicate that the radius of influence of VEW-2 is approximately 125 feet at a flow rate of 51 SCFM. The radius of influence of VEW-1 is approximately 110 feet at a flow rate of 65 SCFM. The smaller radius of influence recorded for VEW-1 could have resulted from the preferential flow of air through the more permeable soils in the backfilled excavation. The less restricted flow through this area would tend to decrease the average radial vacuum and the radius of influence.

TABLE 1

INITIAL SOIL GAS CONDITIONS

VMP	O_2 (%)	CO_2 (%)	PID (ppmv)	TPH-d (mg/kg)	Volatile TRPH (mg/l air)
1	8.4	4.7	10	ND	20
2	0.0	7.8	140	1100	620
3	0.0	7.7	171	ND	840
4	0.8	7.0	NT	580	NT
5	0.1	7.1	71	ND	360
6	1.9	4.4	19	ND	NT
7	10.2	4.2	4	ND	NT
8	8.5	4.5	138	ND	NT
9	7.5	4.3	43	ND	NT
10 (Background)					

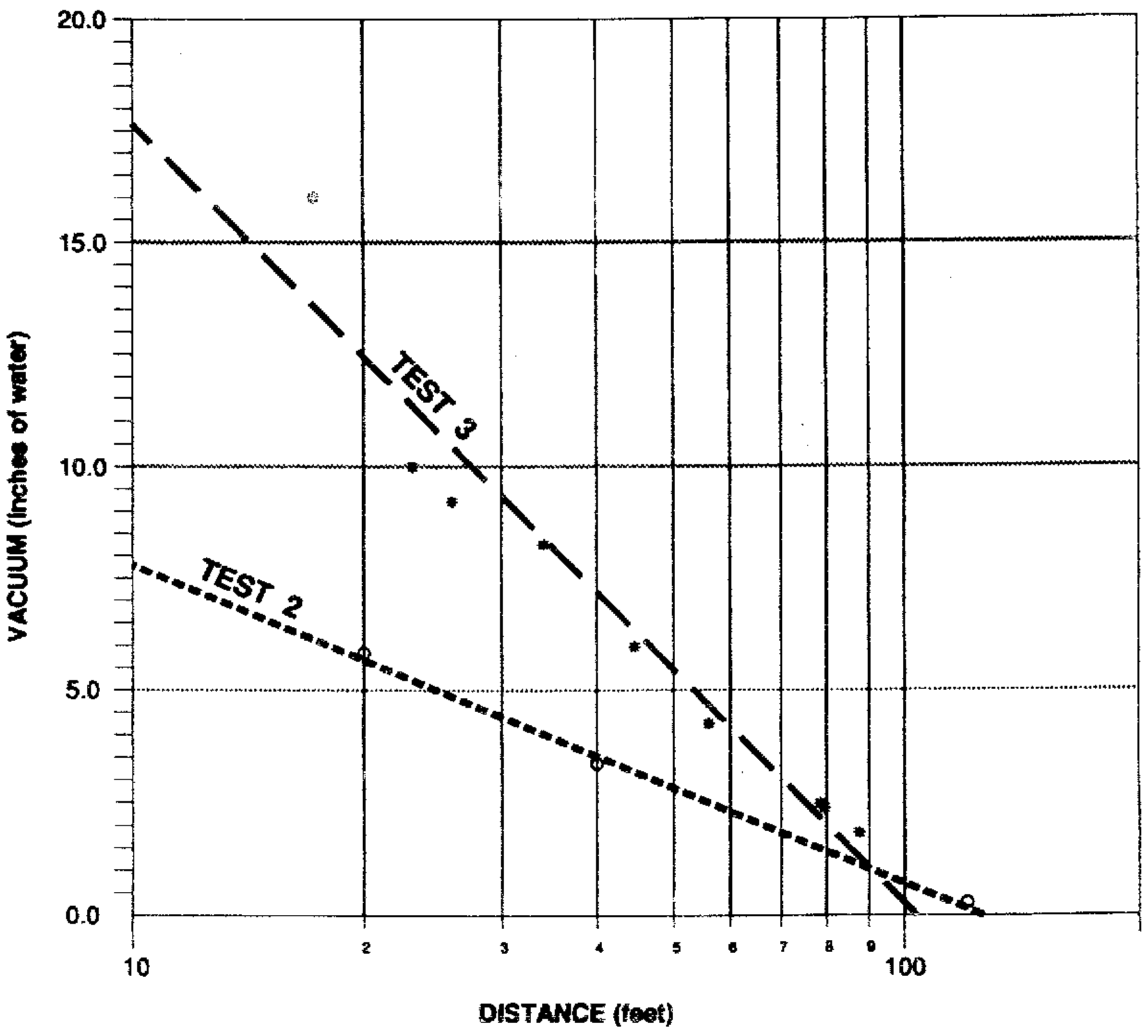
NT = Sample Not Taken
ND = Not Detected
PPMV = Parts Per Million by Volume
TRPH = Total Reportable Petroleum Hydrocarbons
TPHd = total Petroleum Hydrocarbons
PID = Photoionization Detector

TABLE 2

RESULTS OF 30-HOUR SOIL AERATION

VMP	Initial 0_2 (%)	Aerated O_2 (%)	VMP Screen Depth (ft)	Distance From VEW 1 (ft)
1	8.4	11.2	27.5 - 29.5	50
2	0.0	8.2	18 - 20	20
3	0.0	15.0	13 - 15	20
4	0.8	14.3	14 - 16	40
5	0.1	4.0	38 - 40	35
6	1.9	16.3	30 - 32	45
10 (background)	16.0	16.0	14 - 16	200

FIGURE 3



TEST 2
36 SCFM, 39 MINUTES

	DISTANCE FROM VACUUM VEW2 (ft)	in. of H_2O
VMP1	120	0.03
VMP7	40	3.40
VMP8	20	5.80

TEST 3
65 SCFM, 44 MINUTES

	DISTANCE FROM VACUUM VEW2 (ft)	in. of H_2O
VMP1	56	4.2
VMP2	17	16.0
VMP3	23	10.0
VMP4	26	9.2
VMP5	34	8.3
VMP6	45	5.9
VMP7	87	1.85
VMP8	79	2.40
VMP9	78	2.45

SITE 22-A20
DISTANCE VS. VACUUM
BIOVENTING PILOT TEST

Soil permeability was calculated using two methods as described in Johnson et. al. (1990). The calculated soil permeability values for the entire VEW-1 screened interval ranged from 5.6 to 8.4 darcy using the dynamic [redacted] was 8.0 darcy using the steady-state [redacted] The values for VEW-2 ranged from 2.5 to 8.3 darcy using the dynamic method and 1.4 darcy using the steady-state method. A permeability (k) value on the order of 0.1 to 1 darcy corresponds to silty soils (Johnson et. al. 1990). This indicates that sand layers within the site soils have increased the average air permeability by at least one order of magnitude above the k value predicted from grain size analysis.

An oxygen increase was also measured in the exhaust of the ventilation blower, which represents an average of the total soil gas exchange. Exhaust oxygen concentrations increased from 5 percent to over 13 percent during the soil aeration test. [redacted]

In Situ Respiration Test

An additional test measured the utilization of oxygen by existing soil bacteria once this additional oxygen had been supplied. Figure 4 depicts the bacterial uptake of oxygen in contaminated soils (VMPs-2, 3, and 4) compared to the oxygen uptake in two uncontaminated monitoring points (VMPs-1 and 10). In order to biodegrade one pound of fuel hydrocarbon to carbon dioxide and water, approximately 3.5 pounds of oxygen is required. Using this conservative relationship, the quantity of fuel that can be degraded under oxygen-enhanced conditions can be estimated. For this site, an average fuel biodegradation rate of 850 mg of fuel per kilogram of soil per year was estimated. This rate of *in situ* biodegradation is in agreement with field testing conducted by other researchers who have measured biodegradation rates at 300 to 7,000 mg fuel per kilogram of soil per year (Hoeppel et. al. 1991). Natural levels of nitrogen and phosphorus at this site appear to be sufficient to sustain this rate of biodegradation.

FULL-SCALE INSTALLATION

The bioventing technology was successfully tested on this site despite a predominance of low permeability silt and clay soils and contamination extending to a depth of 40 feet. Because the pilot test vent well VEW-1 was capable of providing oxygen to the entire contaminated soil volume, this well was converted into a full-scale bioventing well. A positive displacement blower that is capable of extracting or injecting 40 scfm at 5 psi has been installed on the site for long-term bioventing remediation. Based on a maximum residual fuel concentration of 1,200 mg TPH/kg soil and an average biodegradation rate of 850 mg TPH/kg soil/year, a remediation time of 18 to 24 months at a total cost of less than $20 per cubic yard was estimated. Quarterly O_2, CO_2 and soil gas monitoring will be conducted at the site to determine how biodegradation rates vary with soil temperature and treatment time. After approximately two years of treatment, soils at the site will be resampled to confirm the target level of <100 mg/kg TPH cleanup that has been achieved. The presence of oxygen and fuel degrading bacteria at the 35-40 feet depth will reduce the influx of hydrocarbons to the groundwater and promote the degradation of groundwater contaminants.

ADDITIONAL BIOVENTING RESULTS

Since the case study was completed in 1992, Engineering-Science has completed over 20 additional bioventing pilot tests on Air Force installations. Table 3 illustrates the radius and depth of oxygen influence that has been achieved in a variety of soil types across the United States. These data clearly indicate that oxygen supply and *in situ* bioventing potential is not limited to sandy and high permeability soils.

FIGURE 4: ENHANCEMENT UTILIZATION BIOVENTING PILOT TEST

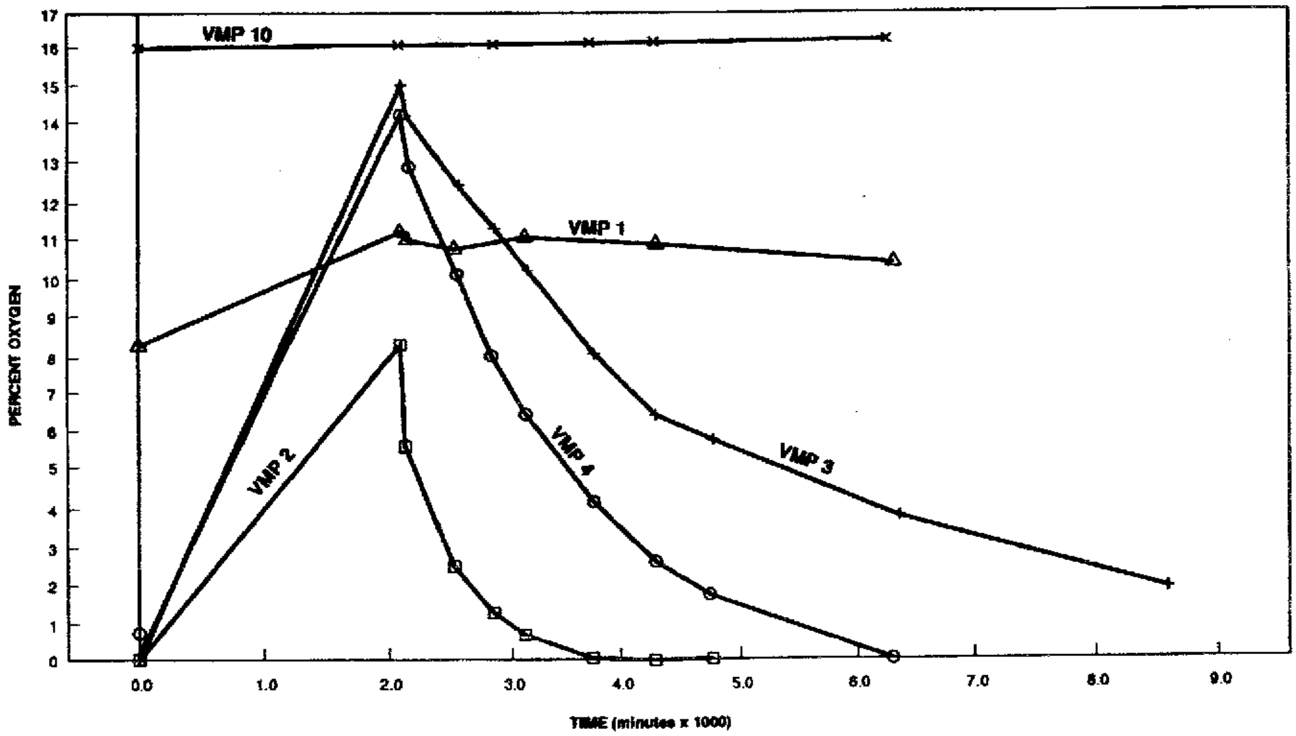


TABLE 3

AFCEE BIOVENTING INITIATIVE OXYGEN INFLUENCE RESULTS

BASE	SOIL	DEPTH (ft)	BIODEGRADATION RATE mg TPH/Kg SOIL/DAY	RADIUS OF INFLUENCE (ft)
F.E. WARREN, WY	SL/CL	11	1.6-5	35+
OFFUTT, NE	SL/CL	9	11	25+
BEALE, CA	SL/CL	40	0.5-1.6	50
KELLY, TX	SL/CL	16	15.4-20.4	30+
VANDENBERG, CA	SA/SL	9	2.2	40
HILL, UT	SA/SL	40+	0.35-12.6	40
PLATTSBURGH, NY	SA	35	13	100+
K.I. SAWYER, MI	SA	65	1.7	60+
BATTLE CREEK, MI	SA	30	5.5	50+
McGUIRE, NJ	SL	14	2.5	20
TINKER, OK	SA	17	1.8	30+
CHARLESTON, SC	SA	4	2.1	30
EGLIN, FL	SA	6	3-5	40

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