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Final Technology Report for D-Area Oil Seepage Basin Bioventing Optimization Test, Environmental Restoration Support

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Executive Summary

One method proposed for the cleanup of the D-Area Oil Seepage Basin was in situ bioremediation (bioventing), involving the introduction of air and gaseous nutrients to stimulate contaminant degradation by naturally occurring microorganisms. To test the feasibility of this approach, a bioventing system was installed at the site for use in optimization testing by the Environmental Biotechnology Section of the Savannah River Technology Center. During the interim action, two horizontal wells for a bioventing remediation system were installed eight feet below average basin grade. Nine piezometers were also installed. In September of 1996, a generator, regenerative blower, gas cylinder station, and associated piping and nutrient injection equipment were installed at the site and testing was begun. After baseline characterization of microbial activity and contaminant degradation at the site was completed, four injection campaigns were carried out. These consisted of 1) air alone, 2) air plus triethylphosphate (TEP), 3) air plus nitrous oxide, and 4) air plus methane. This report describes results of these tests, together with conclusions and recommendations for further remediation of the site.

Natural biodegradation rates are high. Oxygen, carbon dioxide, and methane levels in soil gas indicate substantial levels of baseline microbial activity. Oxygen is used by indigenous microbes for biodegradation of organics via respiration and hence is depleted in the soil gas and water from areas with high contamination. Carbon dioxide is elevated in contaminated areas (the biodegradation of organics produces large amounts of carbon dioxide). High concentrations of methane, which is produced by microbes via fermentation once the oxygen has been depleted, are found at the most contaminated areas of this site. Groundwater measurements also indicated that substantial levels of natural contaminant biodegradation occurred prior to air injection. This was evidenced by an observed decline in chlorinated solvent levels to below detection limits during the baseline monitoring period. Both chloride and sulfate levels were elevated, especially in downgradient wells. Chloride is produced as an end-product of biodegradation of chlorinated solvents, while the presence of sulfate is attributed to microbial degradation of petroleum compounds. An increase in redox potential and decrease in conductivity in downgradient groundwater over the course of the study suggests that microbial activity may have reduced the mobility of metal contaminants emanating from the basin. Groundwater samples from the area were found to contain moderate numbers of bacteria.

During air injection, rates of PCE and possibly TCE degradation in the soil of the basin increased, as shown by soil gas measurements. Analysis of soil surface emissions indicated that removal of VOC's was not simply the result of air stripping. PCE degradation rates averaged 1.7 ppb/day in all but the most highly contaminated area during injection. However, air injection

was most effective at the four corners of the basin, while transfer of oxygen or a helium tracer to piezometers located in the central area was severely limited. This led to lower degradation rates in the unaerated regions and a tendency for chlorinated solvents to be incompletely degraded.

The absence of phosphate in groundwater near the basin suggested that injection of air plus triethylphosphate (TEP) would be of value in enhancing microbial activity. TEP did in fact enhance respiration rates and PCE degradation in the portion of the site containing the highest chlorinated solvent levels. It also led to a decline (compared to air alone) in oxygen levels of soil gas in most areas of the site, suggesting increased microbial metabolic rates. Little or no additional benefit was provided by adding nitrous oxide (as a nitrogen source) or methane (to provide a substrate for methanotrophs which could then carry out a cometabolic degradation of chlorinated solvents). Indeed, microbial respiration rates declined during the latter two injection campaigns. Oxygen was consumed at a mean rate of 0.28 $\%O_2/h$ (corresponding to 4.2 mg total petroleum hydrocarbons/kg soil/day) during air or air plus TEP injection, but this rate dropped to 0.12% O_2/h h (corresponding to 1.8 mg total petroleum hydrocarbons/kg soil/day) by the end of the study. This suggests that the better part of the microbial community may have been substrate limited.

In conclusion, natural (intrinsic) biodegradation rates at the DOSB are relatively high and this has already accomplished considerable remediation of the site. The injection of air plus TEP is recommended to achieve maximum cleanup rates and groundwater protection, but intrinsic bioremediation may be an acceptable solution if time is not a driver. Based on an estimated chlorinated solvent soil gas content of 211 ppb, the observed PCE degradation rate of 1.7 ppb/day would result in cleanup of these compounds after a minimum of 124 days (approximately 4 months) of air/TEP injection. Achieving maximal rates would, however, depend on adequate aeration of the soil. It is suggested that additional injection wells be installed in areas exhibiting poor air transfer. Recommended air flow rate is approximately 100 scfm, in order to achieve a minimum average radius of influence of 15 feet for each of the two 380-foot horizontal wells , corresponding to a minimum total affected soil volume of 5.4×10^5 ft^3. TEP should be added at concentrations of not more than 0.007% (v/v) and should be discontinued when no further stimulatory effect is observed. The injection of methane (4% v/v in air) will be required if PCE, TCE, and PAH's persist after a reasonable period of bioventing.

Background

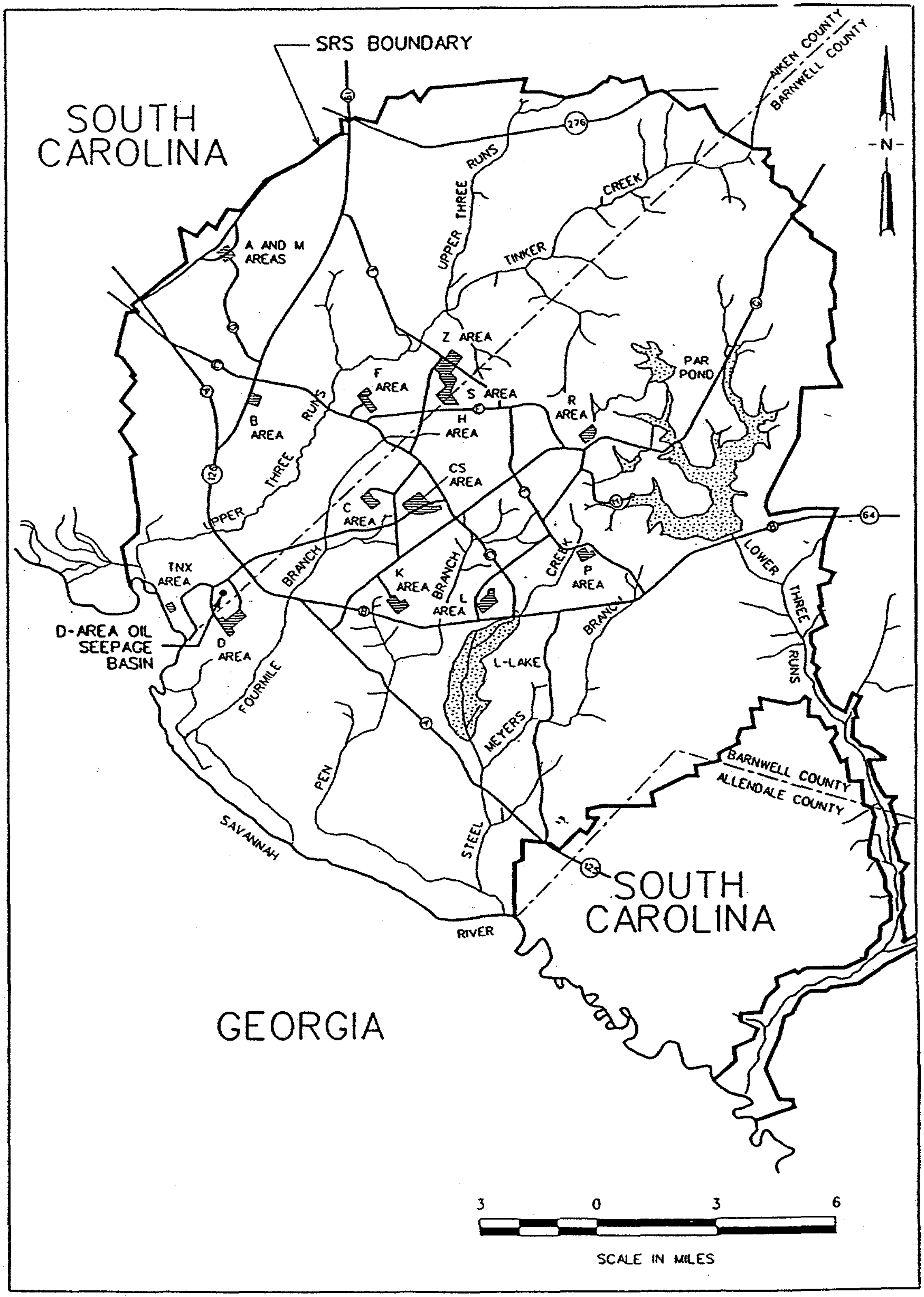
The D-area Oil Seepage Basin (DOSB) is defined as the waste unit located between unimproved dirt Roads A-4.4 and A-4.5, approximately 1.6 km (1 mile) north of the coal-fired D-Area Powerhouse and approximately 3 km (1.9 mile) from the nearest SRS boundary (Fig. 1). It was originally constructed in 1952 as a series of unlined trenches to dispose of waste oils and other fluids not suitable for burning in powerhouse boilers.

The basin received waste oil products from D Area and other areas on-site that were unacceptable for incineration in the powerhouse boilers. These products included seal oil from the Heavy Water Facility, machine cutting oil, and transformer and other shop fluids. The waste oils and fluids were collected in 208-liter (55-gallon) drums, transported to the basin, opened and dumped into the trenches. These materials were periodically burned along with general office and cafeteria waste. This practice continued until 1973 when open burning ceased at SRS. The DOSB continued to receive waste oils and evidently some chlorinated solvents until 1975 when the basin was removed from service and backfilled with soil.

Under the requirements of CERCLA and the FFA, the DOSB is slated for additional assessment and perhaps, environmental remediation. An interim action was conducted to facilitate final remedy selection. As part of the interim remedial action, all drums, large debris, and principal threat source material were removed during April, May, and June of 1996. During these activities, soils down to eight (sometimes twelve) feet below grade were excavated and sieved to remove debris. Excavated soils were exposed to the atmosphere for a period of time, then raked or pushed back into the previously excavated quadrants. Obviously contaminated soils were mainly placed in the northwestern corner of the excavation.

One method proposed for the cleanup of the DOSB was in situ bioremediation (bioventing), involving the introduction of air and gaseous nutrients to stimulate contaminant degradation by naturally occurring microorganisms. To test the feasibility of this approach, a bioventing system was installed at the site for use in optimization testing by the Environmental Biotechnology Section of the Savannah River Technology Center. During the interim action, two horizontal wells for a bioventing remediation system were installed eight feet below average basin grade. Nine piezometers were also installed. In September of 1996, a generator, regenerative blower, gas cylinder station, and associated piping and nutrient injection equipment were installed at the site and testing was begun. This report describes results of the of the optimization test, together with conclusions and recommendations for the further remediation of the site.

Figure 1. Location of D Area in relation to Savannah River Site



Hydrogeology, Contaminants, and Plume Extent

The DOSB is in a low lying wetlands area of SRS. Water table depth varies from 4 to 14 feet (usually about 8 feet). The nearest surface water feature is a Carolina bay, a natural wetland located approximately 61 m (200 ft) west of the unit. Other wetlands exist approximately 137 m (450 ft) to the south of the unit. Groundwater flows in a southerly direction towards a stream and the Savannah River at an average linear velocity of 0.07 ft/day. A potentiometric map of the water table is shown in Fig. 2. The lithology of the DOSB is variable with numerous interbedded sands and clays. A dominant clay lens seems to occur at a depth of 8 - 12 foot over most of the site.

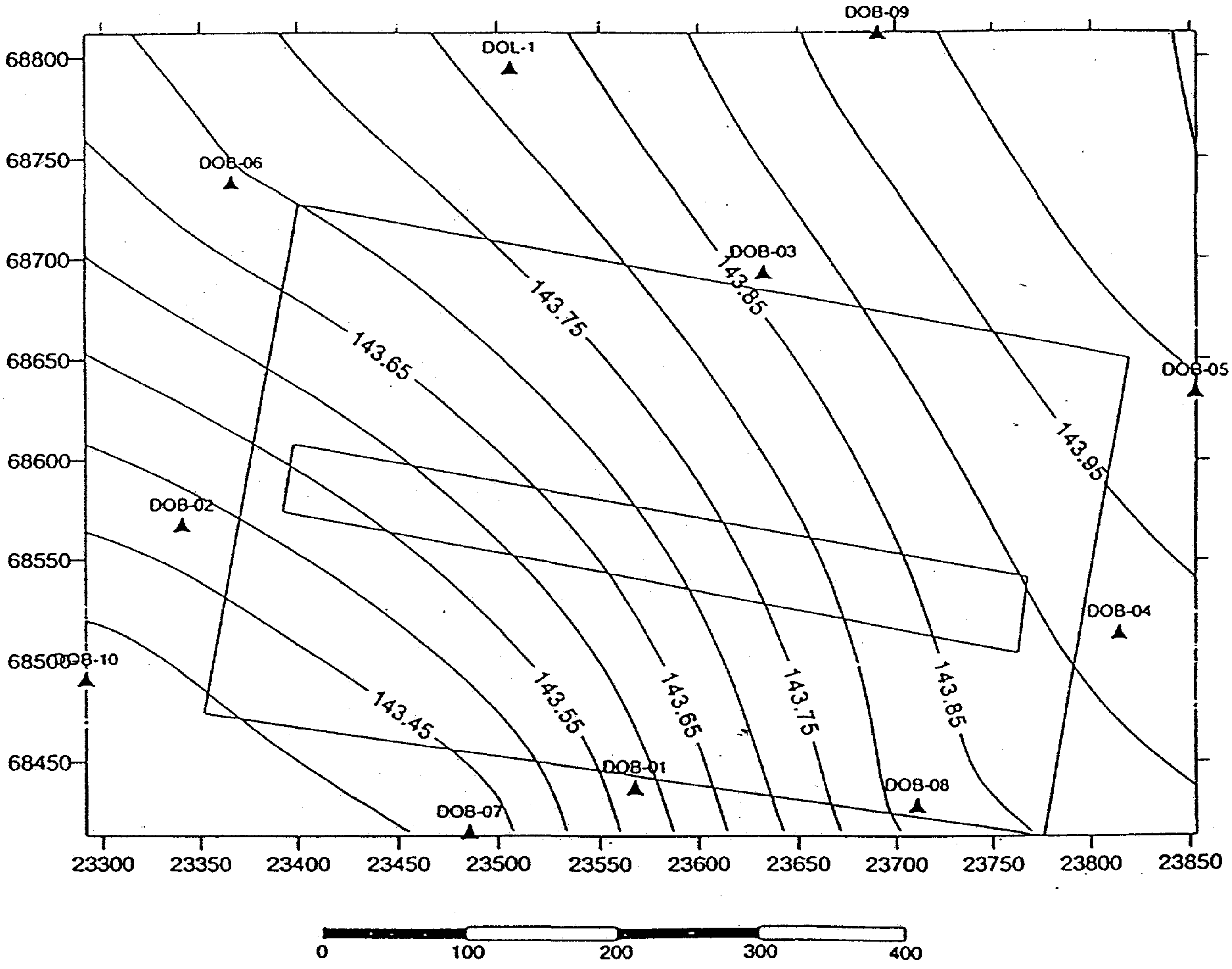
Results of extensive monitoring in the DOSB indicate the presence of various metals, volatile organic compounds, and semi-volatile organic compounds in soil and groundwater (see WSRC, 1994). Organic compounds included trichloroethylene (TCE), tetrachloroethylene (PCE), vinyl chloride, 2-methylnaphthalene, acetone, methylene chloride, 4-methyl-2-pentanone, alkyl benzenes, polynuclear aromatic hydrocarbons (PAHs), phthalate, pesticides, polychlorinated biphenyls (PCBs), and the congeners di-benzo-p-dioxin and di-benzo-p-furan. Also identified were fractions of oil and oil compounds including benzene, toluene, ethylbenzene, xylene, and naphthalene.

TCE and vinyl chloride groundwater plumes were partially characterized during 1995, using CPT and groundwater monitoring wells. Both plumes extend in a southerly direction from the unit and their leading edges are not yet completely characterized.

Test Plan Rationale and Objectives

The D-area Oil Seepage Basin was used for disposal of petroleum-based products and apparently at least some solvents (TCE/PCE). Previous characterization has shown that much of the TCE/PCE has already been converted to vinyl chloride by anaerobic bacteria present in the soil. These findings suggest an environment that is oxygen limited and is already actively degrading the petroleum contaminants present. The introduction of air could potentially increase the biodegradation rate of the remaining petroleum components and stimulate the co-metabolic biodegradation of the remaining chlorinated solvents. Studies at the SRS Sanitary Landfill have shown that biostimulation of the soil microbiota in high carbon environments via air injection alone can stimulate the bacteria to biodegrade all BTEX and chlorinated solvents in the groundwater and soil to below detection limits (< 2 ppb). At the SRS Integrated Demonstration Site, gaseous nutrient injection (methane, nitrous oxide, and TEP) in conjunction with air

Figure 2. Potentiometric map of the water table, D Area Oil Seepage Basin



injection has been demonstrated to enhance TCE biodegradation (WSRC, 1993; Hazen et al., 1994). Thus, the focus of this test was to determine the intrinsic rate of bioremediation at the site and the ability of air injection to enhance the in situ biodegradation rate of the contaminants of concern. The effect of injecting nutrients in gaseous form was compared with that of air alone. Data gathered from this test will be used in determining a final disposition/remediation strategy for the site.

The objectives of the D-area Oil Seepage Basin test were as follows:

1. Determine the intrinsic rate of biodegradation of organics in the soil and groundwater.
2. Determine the biodegradation rates of contaminants of concern in the soil and groundwater during biostimulation from air and gaseous nutrient injection.
3. Establish the feasibility of in situ bioremediation of groundwater and soil at the site.
4. Provide data necessary for the functional design criteria for the final remediation system.

Experimental Plan

The study was being carried out in three phases as follows:

Phase I. Baseline Data Collection. Soil gas and groundwater were monitored over an approximately 3-month period (until regulatory approval was obtained for air injection) to assess baseline parameters for the site.

Phase II. In Situ Respiration and Conservative Tracer Determinations. Air and helium (maximum level 1% in air) were injected until steady state was reached and then turned off and monitored until pre-injection conditions resumed. Helium injection was also used to evaluate the uniformity of air transfer to the soil.

Phase III. In Situ Biostimulation Using Air and Gaseous Nutrients. Four injection campaigns were carried out. These were: 1) air injection, 2) air plus triethylphosphate (TEP) injection, 3) air plus nitrous oxide injection, and 4) air plus methane (CH_4) injection. Each campaign involved a 1-week injection period, after which soil gas content, water quality, and respiration rates were determined to assess the effects of biostimulation.

Data from these tests has been used to estimate the biodegradation rates of contaminants of concern in the soil and groundwater, evaluate of the feasibility of in situ bioremediation of soil and groundwater at the site, and establish functional design criteria for the final remediation system.

Methods

Bioventing System

A schematic of the bioventing system is shown in Fig. 3. A Sweetwater S-45 regenerative blower was used to inject air at a maximum rate of approximately 90 - 100 scfm and a pressure of 30 - 35" H_2O. This flow rate is calculated to result in a minimum average 15-foor radius of influence for each well and a minimum total affected soil volume of 5.4×10^5 ft^3. Flow rates to the two 380-foot horizontal wells were individually measured and controlled. During the TEP injection campaign, triethylphosphate was added by continuously sparging a flow-regulated portion of the air through a tank of liquid TEP and then allowing the TEP-saturated air to enter the horizontal wells. Final TEP concentration was 0.00175 - 0.0028% (nom.). In a subsequent campaign, nitrous oxide was added to the air stream at the 0.1% level from compressed gas cylinders. Air injection was continuous, with nitrous oxide being added for 8 h/day for 1 week. Methane injection (4%) was carried out similarly, but was routinely performed for approximately 4 h/day (in order to avoid the establishment of anaerobic conditions). Helium (1%) was sometimes added from compressed gas tanks as a tracer in in situ respirometry tests and for use in establishing gas flow patterns at the site. Operation of the system was carried out in accordance with EPA-recommended practices (EPA, 1995). Projected air emissions of volatile, semivolatile, and Standard 8 contaminants were calculated to be insignificant.

Sampling Locations

Soil gas sampling and pressure measurements were carried out via nine vadose zone piezometers, designated DOB-BV1 through DOB-BV9. These are shown in Figs. 4 and 5. Piezometers extended to a depth of about 5 feet and were screened for the last 2 feet. Details of piezometer construction are shown in Fig. 6. Bundle tubes terminating at 50-foot intervals within the horizontal wells DOB-1HW and DOB-2HW were also occasionally used for gas monitoring (Fig. 4 inset), but these measurements were discontinued during the study because of the risk to sampling equipment posed by the frequent presence of water in the horizontal wells.

Groundwater was sampled via a series of groundwater monitoring wells (DOB 2, 3, 4, 5, 11, 13, 14) located around the periphery of the site. They were selected to include upgradient (DOB 3, 5), side gradient (DOB 2,4) and downgradient (DOB 11, 13, 14) sampling points. Approximate locations of these and other nearby monitoring wells are shown in Fig. 4. Table 1 shows the total depths and screened areas of these wells.

Figure 3. Schematic drawing of bioventing system

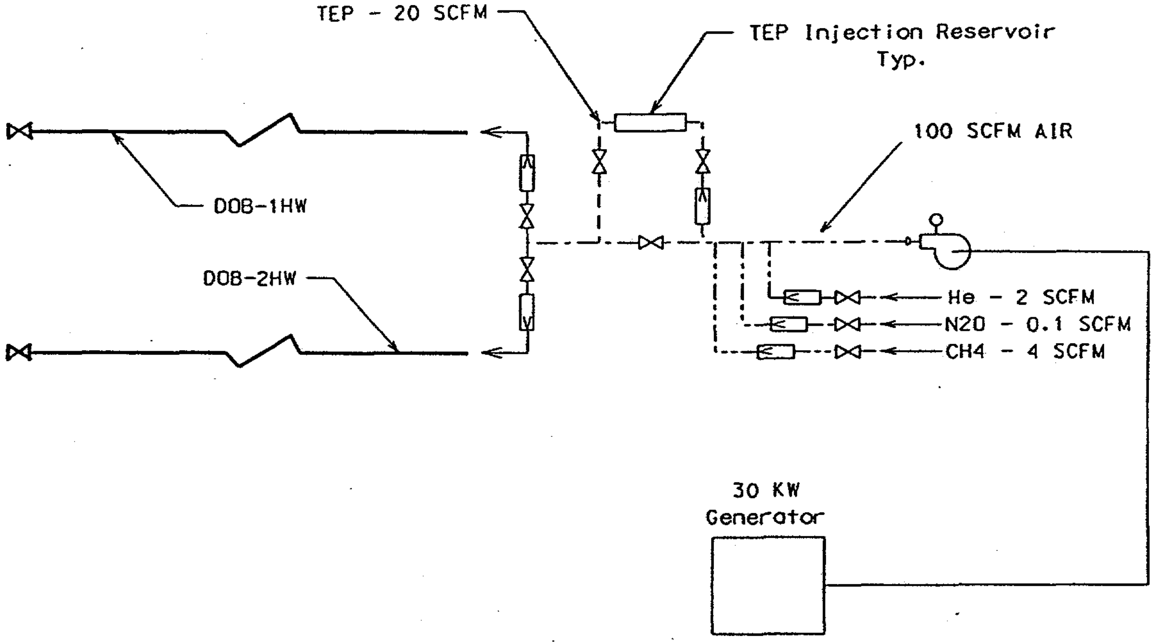


Figure 4. As-built drawing showing horizontal wells and piezometers

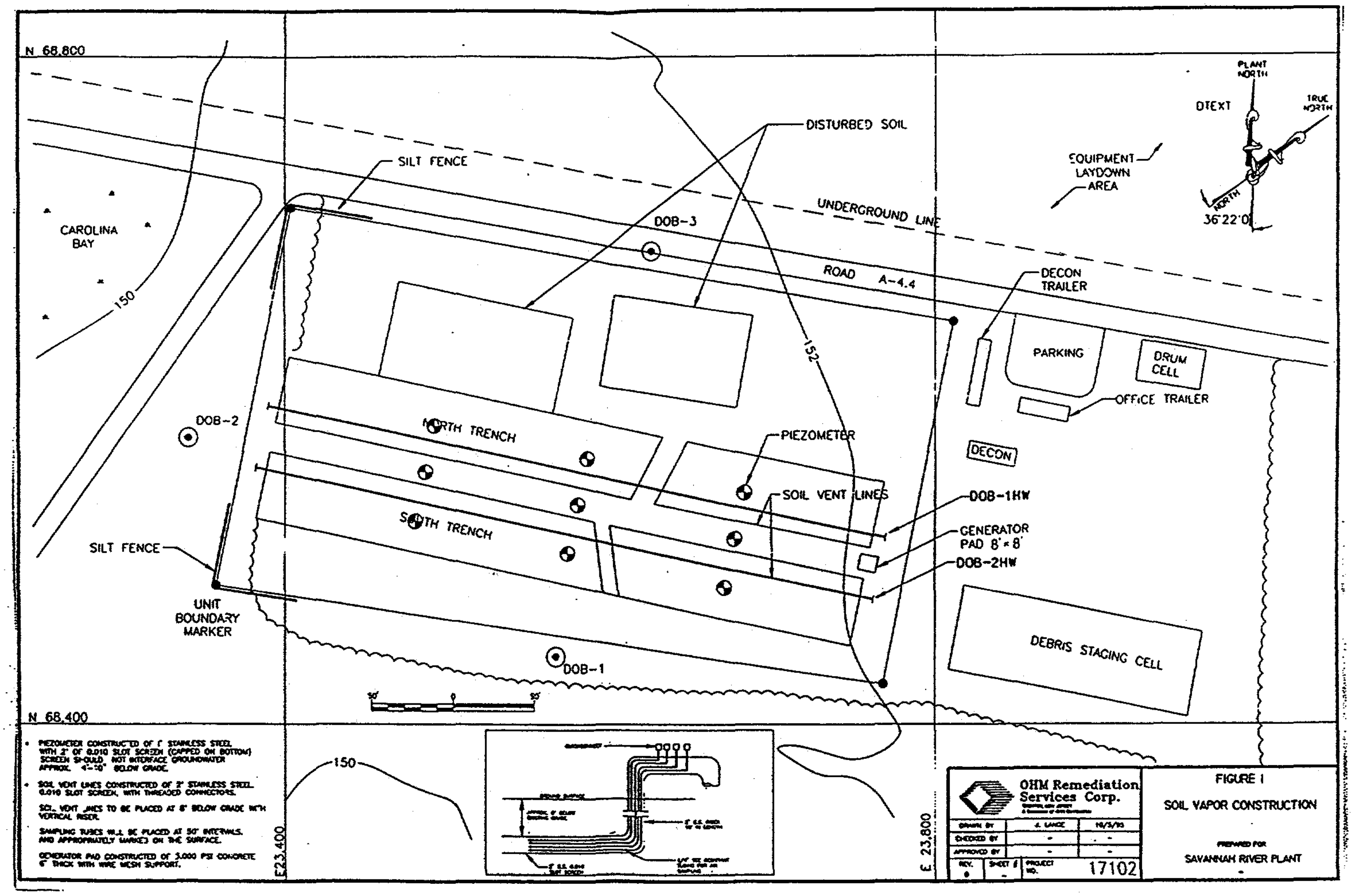


Figure 5. Locations of monitoring wells and piezometers

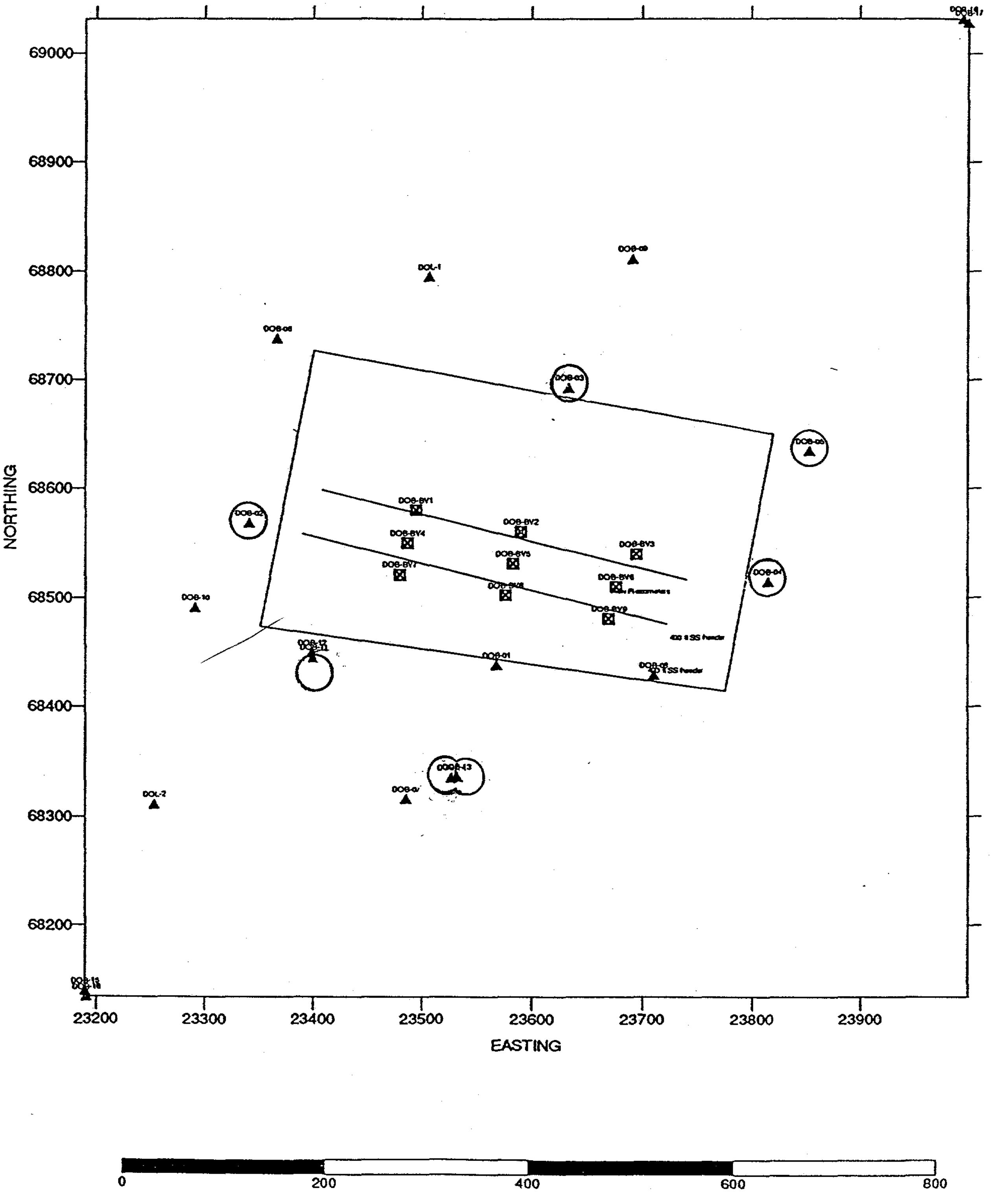


Figure 6. Details of piezometer construction

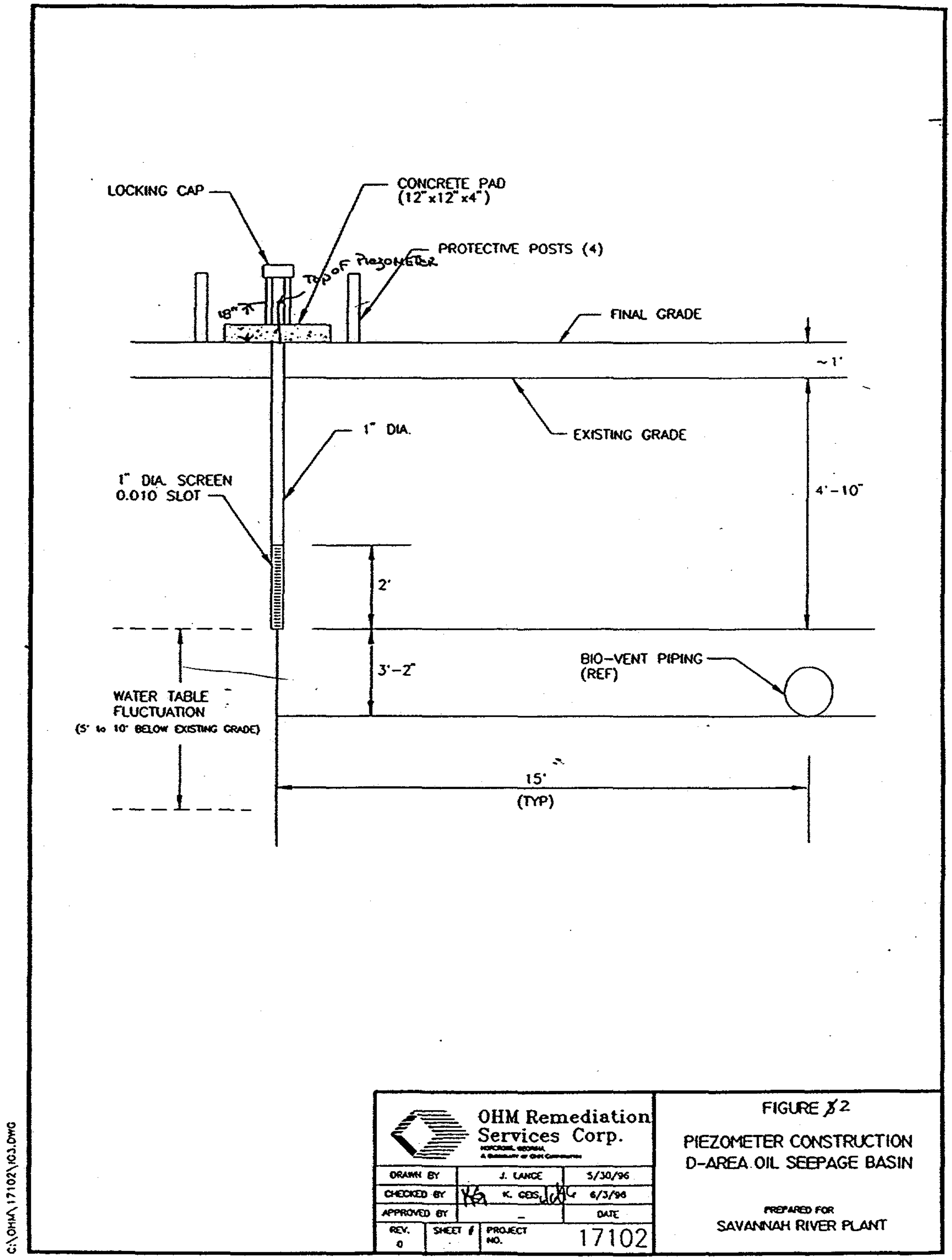


Table 1. Screen zones of monitoring wells.

Well	**Top of Screen (ft)**	**Bottom of Screen (ft)**
DOB-2	5	35
DOB-3	5	35
DOB-4	12	42
DOB-5	3	23
DOB-11	18.7	23.7
DOB-13	18.5	23.5
DOB-14	11.7	16.7

Experimental Procedures

Monitoring of soil gas and groundwater was performed during the July 18 - September 26, 1996 period to establish baseline parameters for the site prior to the start of bioventing. After baseline measurements of soil gas and groundwater (Phase I) had been completed, air injection (45 scfm/horizontal well) was commenced on September 30, 1996 in preparation for in situ respiration and conservative tracer testing (Phase II). The increase in oxygen levels was measured at all piezometers during the injection, and air flow was stopped when oxygen concentrations appeared maximal (after 3 days' continuous injection). The subsequent decrease in oxygen levels was then monitored over a 44-h period in order to establish oxygen consumption rates for the site. These rates were then used to calculate estimated rates of petroleum hydrocarbon oxidation.

After the initial respirometric test had been concluded, air injection recommenced on October 5, 1996) in an attempt to stimulate microbial biodegradation by prolonged enhancement of oxygen levels in the soil gas (Phase III). During this time, a helium tracer test (Phase II) was carried out. The inert gas was added to the air stream (at about the 1% level) for 4 hours and the rise in helium concentrations at the piezometers was measured. Helium concentrations in the injected air were monitored by periodically opening the valve at the end of horizontal well DOB-2HW to allow insertion of a helium probe into the air stream.

Continuous air injection was carried out for 5 days (in addition to the 3 days of injection prior to respirometric measurements). At the conclusion of this injection campaign, all gas and water monitoring and analyses were repeated for comparison with baseline values. Gas samples were collected both while air was being injected and after the system had been turned off for several days.

During the final 4 hours of air injection (October 10, 1996), 1% (nominal) helium was again added to the air stream as a tracer. Air and helium injection was then discontinued, and a second respirometric test was performed to determine if any enhancement of hydrocarbon degradative potential had occurred. This test was performed in the same manner as the previous one, except that helium as well as oxygen concentrations were measured at each time point to assess the influence of surface air diffusion on soil gas content.

The TEP/air injection campaign was carried out during the October 22 - 31 period. Injection was interrupted twice during this time due to generator outages, and total injection time is estimated at 6.5 - 7 days. Nitrous oxide/air injection was performed from November 8, 1996 to

November 15, 1996 (7 days of air injection), with the total nitrous oxide injection time being 52 h (5 - 8 h/day). Methane injection was carried out from November 21, 1996 to November 27, 1996 (6.2 days air injection), with total methane injection time being 29 h (averaging 4.1 h/day). For safety reasons, methane levels in the injected air were monitored at 2-h intervals and flow was adjusted so than methane levels did not exceed 4% (LEL = 5%). Methane levels in the cylinder shed (floor level) were similarly monitored as a precaution against leakage. Each campaign was immediately followed by a respirometric test, conducted as described above. 1% (max.) helium was added to the air stream for use as a tracer for several hours prior to each test. On the final day of each campaign, all groundwater monitoring wells and piezometers were monitored and sampled. A second set of soil gas samples were taken in each case after the injection system had been turned off for several days.

A second, longer term tracer study of air transfer patterns at the site was performed during the November 12 - 15 period (simultaneously with nitrous oxide injection). In this test, He (1%) was added to the air stream for approximately 8 h/day on three consecutive days. He levels were measured on a daily basis at each piezometer and at the far end of horizontal well DOB-HW2.

Emission of volatile organics from the soil surface at the site was measured on December 4, 1996. These measurements were performed both during air injection (1 h) and with the injection system turned off.

Analytical Methods

Soil Gas Measurements. A Landtec GEM-500 gas extraction monitor was used in the field to measure CH_4, CO_2, and O_2 in soil gas from the vadose zone piezometers. Pressure in the piezometers was also measured using this instrument. Helium levels were measured by means of a Mark Products Model 1820A helium detector. A vacuum pump was used to provide a stream of soil gas for monitoring; prior to recording measurements the piezometers were purged for 2 min or until stable readings were obtained. Soil gas samples were collected in Tedlar gas sampling bags (Supelco, Inc.), placed in a cooler, and transported to the laboratory to be analyzed within 24 h for VOC (volatile organic compounds). VOC content of the samples was analyzed using a Hewlett-Packard 5890 gas chromatograph equipped with a 75 nm diameter Vocol column, operated with splitless or 1:1 split injection, a 5 ml/min flow rate, and a 50 ml/min purge rate, and either an electron capture detector or an electron capture detector plus a flame ionization detector; or a Hewlett Packard 5890 Series II gas chromatograph equipped with an electron capture detector and a 60 m, 0.32 nm diameter Vocol column, operated with splitless injection, a 0.870 ml/min flow rate, and a 50 ml/min purge rate.

Emission of volatile organics from the soil was measured using a flux chamber and an infra-red analyzer (Bruel & Kjaer type 1302 infra-red photoacoustic multi-gas monitor).

Groundwater Measurements. Groundwater characteristics were measured during baseline assessment and at the end of each injection campaign. A HydroLab Scout 2/Datasonde 3 multiparameter water quality data logger equipped with a flow-through cell was used to analyze water on site for dissolved oxygen, redox potential, conductivity, pH, and temperature. Water samples were then collected, placed in a cooler, and transported to the laboratory for analysis. BTEX, vinyl chloride, dichloroethylene, trichloroethylene, tetrachloroethylene, total petroleum hydrocarbons, and PAH levels were determined using a Hewlett-Packard GC-MS system, consisting of a Model 5890 Series II gas chromatograph equipped with a Series 5972 mass selective detector and a model 7694 headspace sampler. Total petroleum hydrocarbons and PAH were determined following a chloroform extraction. A HP-5 column (50 m length, 0.32 nm diameter) was used. Chloride, nitrate, nitrite, phosphate, and sulfate were quantified using a Dionex Model QIC2 ion chromatograph equipped with an IonPac Fast Anion column. An isocratic elution and a 2.0 ml/min flow rate were used. Microbial analyses (direct enumerations and colony counts) were also carried out on groundwater samples. Total bacterial counts were performed by the Acridine Orange Direct Count (AODC) Method. Appropriate aliquots of sample were stained with acridine orange for 2 min on a 0.2 μm Nuclepore filter in a vacuum manifold, then filtered. The filter was then mounted on a slide on top of a drop of immersion oil. One drop of immersion oil was added on top of the filter and a cover slip applied. Cells were then counted using epifluorescence microscopy and total cell numbers were calculated. Culturable heterotrophic bacteria and petroleum hydrocarbon degraders were enumerated by colony counts. A tenfold dilution series (using phosphate buffered saline) was constructed for each sample. A 0.1 ml aliquot of each dilution was then evenly spread over duplicate plates containing appropriate agar-solidified media. The 1% Peptone-Trypticase-Yeast Extract-Glucose (PTYG) medium of Balkwill (1989) was used to enumerate total culturable aerobic and facultatively anaerobic heterotrophic bacteria. Cyclohexamide was added to the medium to prevent fungal overgrowth. A mineral salts medium (MPN Medium) containing no dissolved carbon source was used to enumerate petroleum hydrocarbon degraders. Inoculated MPN plates were incubated in a desiccator containing a small amount of diesel fuel; the diesel fumes thus provided the sole carbon source (other than the agar itself and carbon sources present in the inoculum). The impact of the latter carbon sources on estimates of petroleum hydrocarbon degrader numbers was assessed by inoculating MPN control plates which were then incubated in the absence of diesel fumes. All plates were incubated 1 week before colonies were counted and bacterial densities calculated.

Results

Soil Gas Measurements

Effectiveness of air transfer. During baseline measurements (before air injection), soil gas contained low oxygen levels and elevated carbon dioxide levels (Fig. 7). Continuous air injection into both horizontal wells (45 - 50 scfm/well) was initiated on September 30, 1996. This caused oxygen to increase to near-atmospheric levels and carbon dioxide levels to decline in soil gas measured at piezometers DOB-BV1, 3, 7, and 9 (see Figs. 4 and 5 for piezometer locations). Positive pressures were also measured at these piezometers. Piezometers DOB-BV2, 5, and 8, however, invariably showed pressure readings at or near zero and did not attain oxygen levels as high as at the corner locations, while DOB-BV4 and DOB-BV6 showed mixed or intermediate results. These data suggested that air flow may not have been as rapid in the central portion of the previously excavated area as near the corners.

To test this idea, we conducted a 4-hour helium tracer test (Fig. 8). Helium was injected at a concentration of approximately 0.9% in air (measured at the far end of horizontal well DOB-2HW, which was opened periodically to permit gas level monitoring). Fig. 8 shows data from two piezometers at well-aerated corner locations (DOB-BV3 and DOB-BV9) as well as from a piezometer showing little elevation in oxygen levels (DOB-BV6). It can be seen that He penetrated rapidly to DOB-BV9 and somewhat more slowly to DOB-BV3, but did not reach DOB-BV6 at all during the duration of the test. Helium reached DOB-BV1 and DOB-BV7, but little effect was seen at DOB-BV2, 4, 5, and 8 (data not shown). These findings further indicate that gas flow through the soil is restricted in the central portions of the contaminated area.

A tracer test of longer duration was conducted in order to elucidate the extent of air flow to the central portions of the DOSB (Table 2). Helium (0.9%, measured at the west end of DOB-HW2) was injected for approximately 8 h/day for 3 days. Table 2 shows that helium levels at piezometers DOB-BV1, 3, 7, and 9 (the corner locations) increased to near their maximal levels within about 6.5 h after He injection commenced. Helium concentrations increased steadily but much more slowly at DOB-BV 6 and 8. They remained below 20% of the input concentration after 3 days' injection. Piezometers DOB-BV 2, 4, and 5 never exceeded 7% of

Figure 7. Soil gas levels at the DOSB during baseline measurements (before air injection).

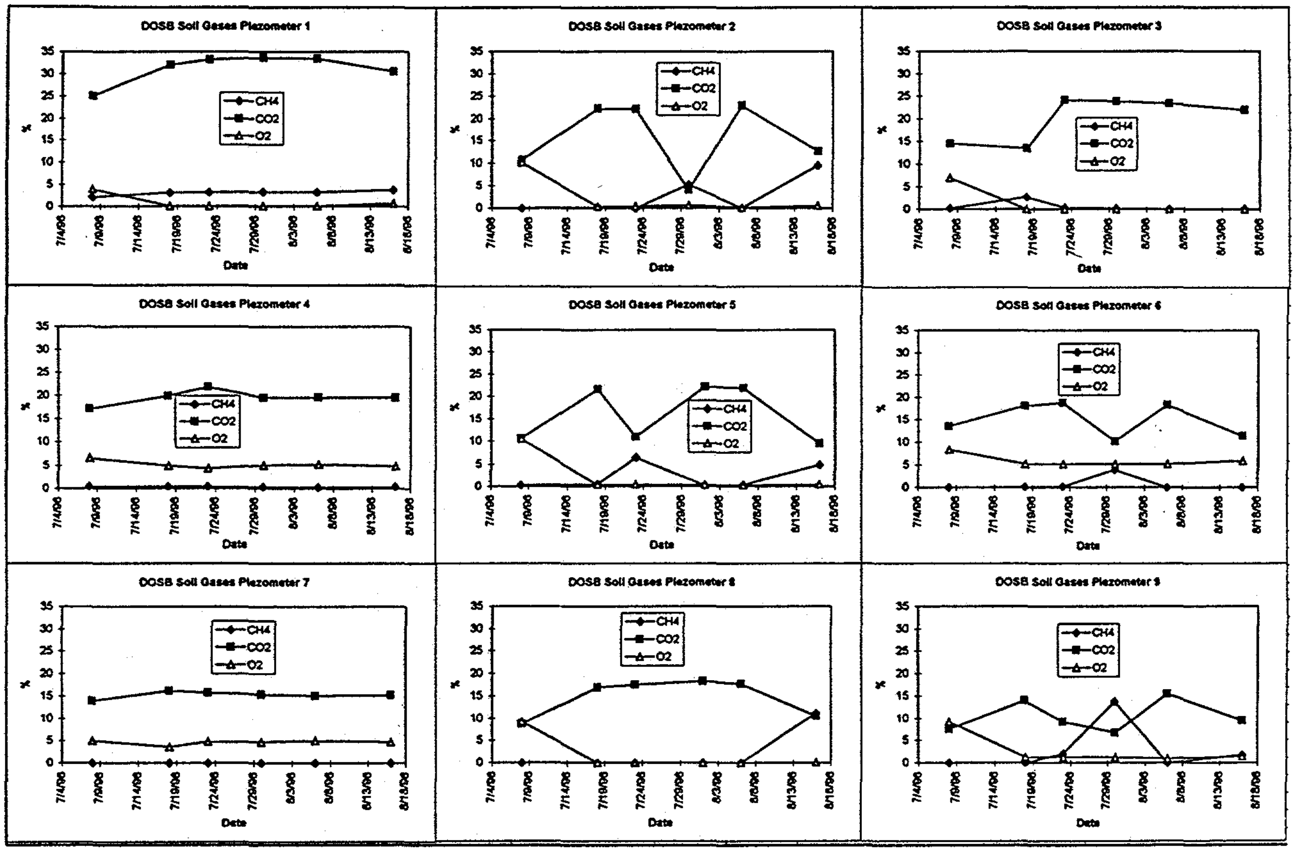


Figure 8. Sample data from helium tracer test

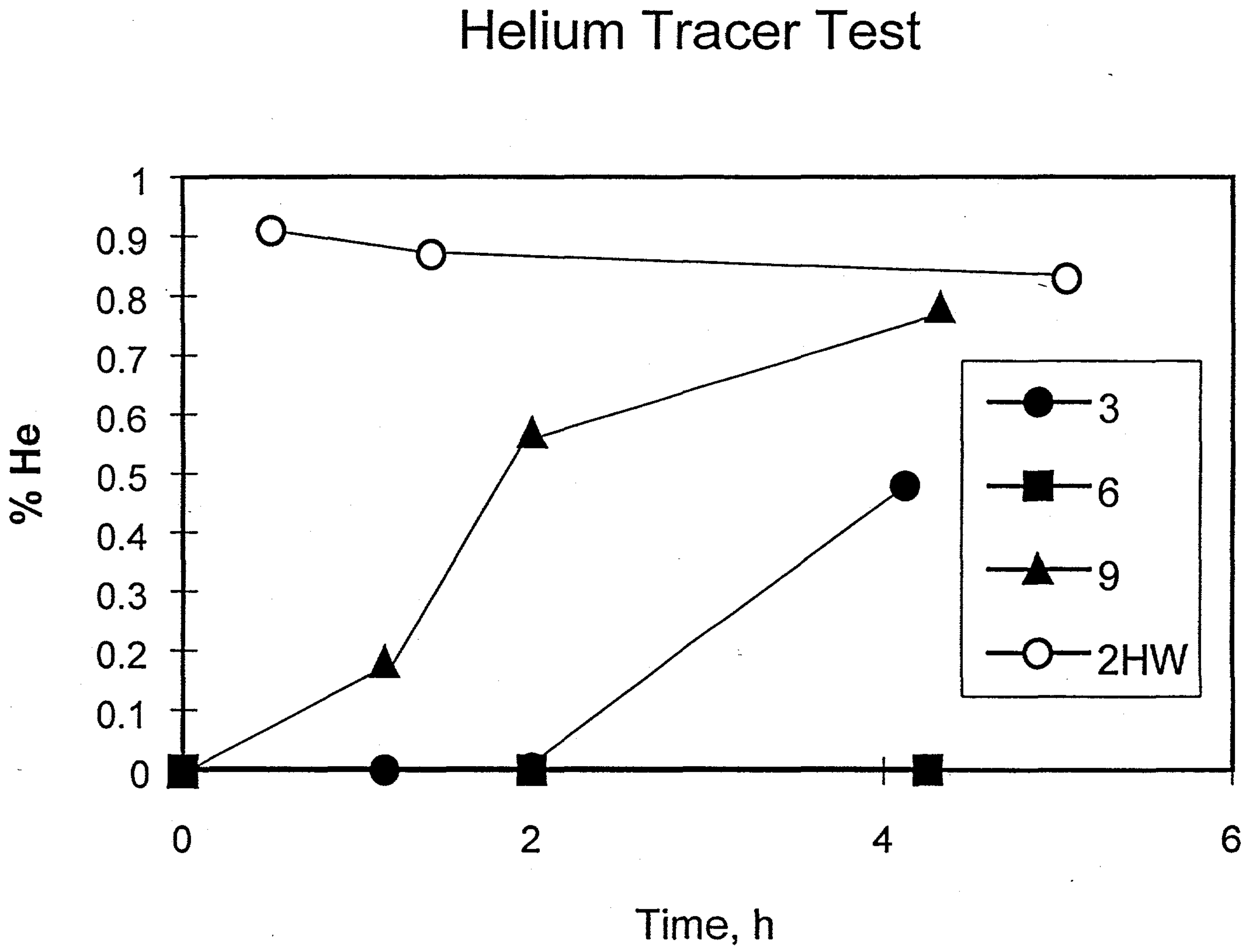


Table 2. Three-day helium tracer test.

Date	**Time**	**DOB-BV1**	**DOB-BV2**	**DOB-BV3**	**DOB-BV4**	**DOB-BV5**	**DOB-BV6**	**DOB-BV7**	**DOB-BV8**	**DOB-BV9**
11/12/96	0856	0	0	0	0	0	0	0	0	0
11/12/96	1520	0.8	0.01	0.78	0.01	0	0.01	0.64	0.02	0.79
11/13/96	1335	0.83	0	0.83	0.07	0.02	0.1	0.69	0.06	0.87
11/14/96	1655	0.73	0	0.72	0	0.02	0.11	0.51	0.09	0.86
11/15/96	1117	0.77	0	0.73	0.04	0.01	0.17	0.56	0.12	0.92

the input concentration and appeared to be undergoing no further increase at the time the test was concluded. Air flow seems severely restricted at these latter locations.

Oxygen and CO_2 levels in soil gas. Baseline soil gas data (Fig. 7) indicate that considerable microbial metabolic activity was present in the DOSB prior to air injection. This is evidenced by the low oxygen levels, elevated carbon dioxide levels, and the presence of methane at most piezometers. These data show that microbial activity consumed all ambient soil gas oxygen and created anaerobic conditions necessary for methanogenic bacteria. Since background soil gas and groundwater oxygen are normally present in the SRS subsurface, excessive amounts of biodegradable organic carbon (contaminants) must have been present at the DOSB. The injection of air caused an increase in oxygen content , a decrease in carbon dioxide content, and the disappearance of methane (except at some piezometers during methane injection) in the soil gas (Appendix 1 lists soil gas data for the entire study). However, differences were seen between the various injection campaigns. Although such differences may reflect abiotic as well as microbially mediated processes, they are suggestive of changes in bacterial oxygen consumption and carbon dioxide evolution as a result of the treatments. These observations are summarized in Fig. 9, which shows mean oxygen/carbon dioxide ratios during the four injection campaigns. It can be seen that, at six of the nine piezometers, the lowest oxygen/carbon dioxide ratios occurred during air/TEP injection, while air alone yielded the lowest ratio at two of the remaining locations.

In situ respirometry. Rates of microbial activity were determined using in situ respirometry. Baseline activity was measured following three days of air injection to raise the oxygen concentration of the soil gas to a level which would allow the test to be performed. At this point, air injection was stopped and the subsequent decline in oxygen and increase in CO_2 were measured over a 44-hour period. Subsequent tests were performed immediately following each 1-week injection campaign. Helium (1% max.) was injected into the air stream during the final hours of each injection campaign, after which the air and helium supply was turned off and oxygen consumption was monitored. Fig. 10 shows typical experimental data, while results of all tests are shown in Table 3. Only oxygen data are shown, since hydrocarbon degradation rates can be more accurately calculated from O_2 consumption rates rather than CO_2 evolution rates, which are influenced by pH and soil type (EPA, 1995). Omitted entries in Table 3 indicate that a piezometer failed to show any consistent trend in oxygen levels and hence that an oxygen consumption rate could not be calculated. Piezometers where this occurred in some or all tests were the same ones (DOB-BV 2, 4, 5, 6, and 8) previously shown to exhibit impaired gas transfer during tracer studies. Table 3 shows oxygen consumption at each piezometer ($\%O_2/h$) as well as estimated total petroleum hydrocarbon oxidation rates per kg soil per day (mg

Figure 9. Mean oxygen/CO_2 ratios during injection campaigns.

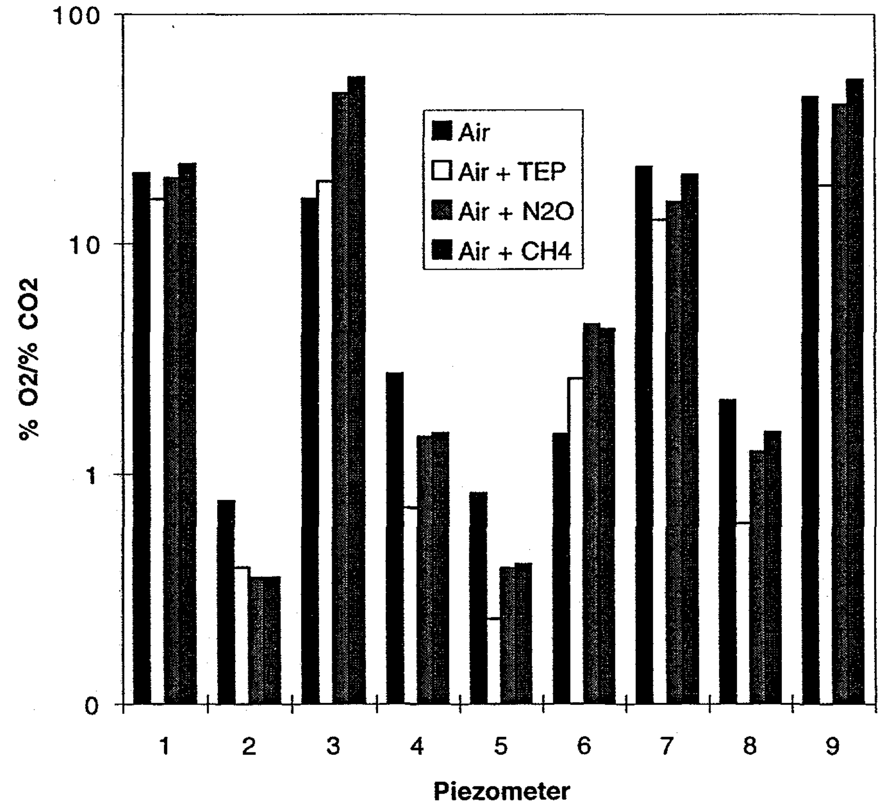


Figure 10. Sample data from in situ respirometry test

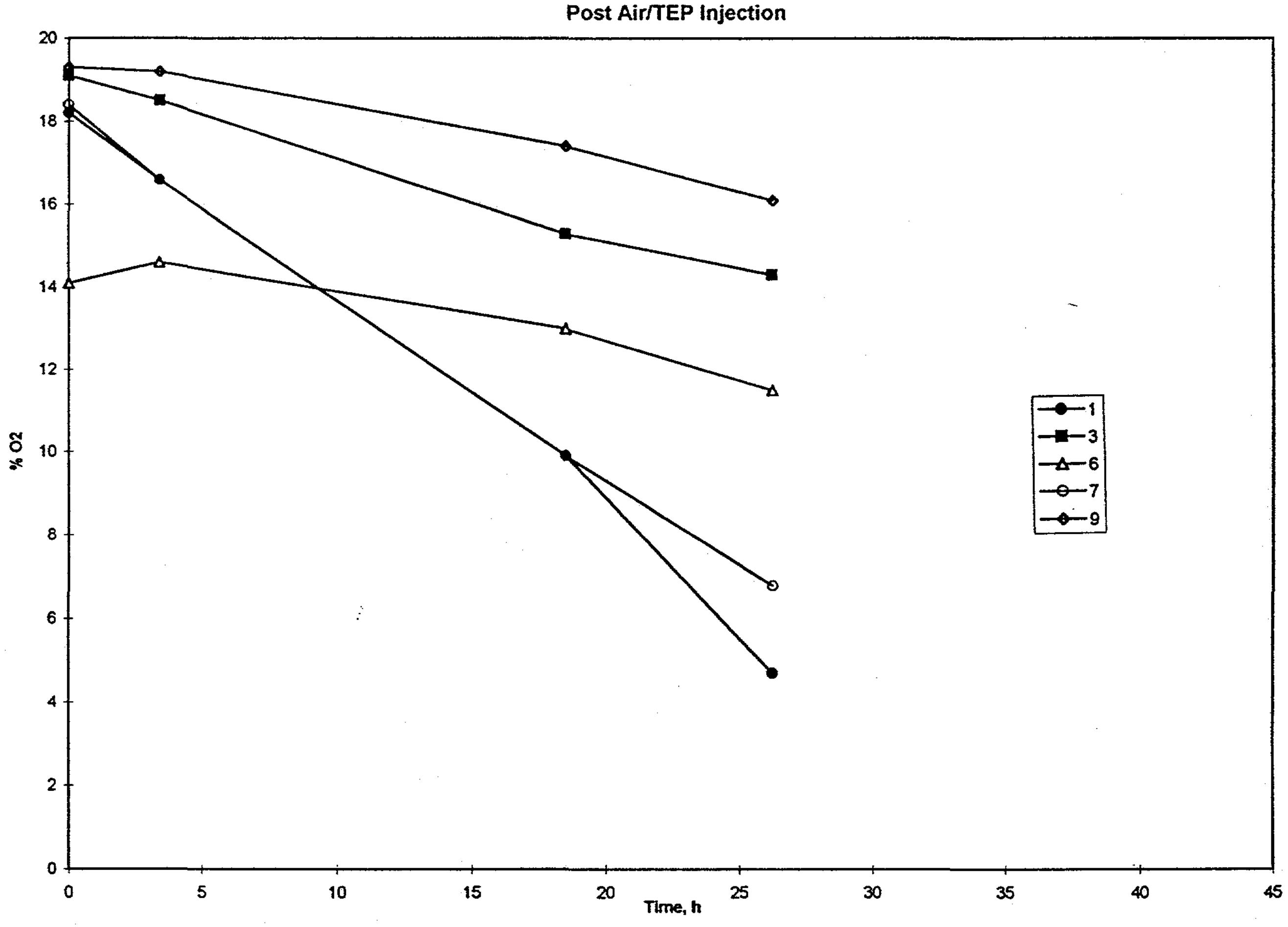


Table 3. Summary of in situ respirometry data

		Piezometer									
		1	2	3	4	5	6	7	8	9	Mean
Baseline	R Square	0.96	*nd*	0.84	0.93	*nd*	*nd*	0.92	0.97	0.97	
	%O2/h	-0.52	*nd*	-0.25	-0.35	*nd*	*nd*	-0.23	-0.10	-0.20	-0.28
	Standard Error	0.04	*nd*	0.04	0.04	*nd*	*nd*	0.03	0.01	0.01	
	mg TPH/kg soil/d	-7.86	*nd*	-3.81	-5.29	*nd*	*nd*	-3.54	-1.45	-3.01	-4.16
Post Air	R Square	0.88	*nd*	0.98	0.56	*nd*	*nd*	0.95	*nd*	0.98	
	%O2/h	-0.53	*nd*	-0.25	-0.22	*nd*	*nd*	-0.31	*nd*	-0.08	-0.28
	Standard Error	0.11	*nd*	0.03	0.11	*nd*	*nd*	0.05	*nd*	0.01	
	mg TPH/kg soil/d	-8.06	*nd*	-3.79	-3.34	*nd*	*nd*	-4.64	*nd*	-1.14	-4.20
Post TEP	R Square	0.99	*nd*	0.99	*nd*	*nd*	0.97	1.00	*nd*	0.98	
	%O2/h	-0.50	*nd*	-0.19	*nd*	*nd*	-0.13	-0.44	*nd*	-0.12	-0.28
	Standard Error	0.03	*nd*	0.01	*nd*	*nd*	0.02	0.01	*nd*	0.01	
	mg TPH/kg soil/d	-7.54	*nd*	-2.85	*nd*	*nd*	-1.99	-6.65	*nd*	-1.85	-4.18
Post N2O	R Square	1.00	*nd*	0.99	*nd*	*nd*	*nd*	0.99	*nd*	0.96	
	%O2/h	-0.29	*nd*	-0.08	*nd*	*nd*	*nd*	-0.28	*nd*	-0.05	-0.18
	Standard Error	0.01	*nd*	0.00	*nd*	*nd*	*nd*	0.02	*nd*	0.01	
	mg TPH/kg soil/d	-4.37	*nd*	-1.25	*nd*	*nd*	*nd*	-4.22	*nd*	-0.74	-2.65
Post CH4	R Square	1.00	*nd*	0.97	1.00	*nd*	0.80	1.00	0.98	0.96	
	%O2/h	-0.29	*nd*	-0.08	-0.10	*nd*	-0.02	-0.25	-0.04	-0.04	-0.12
	Standard Error	0.00	*nd*	0.01	0.00	*nd*	0.01	0.01	0.00	0.01	
	mg TPH/kg soil/d	-4.43	*nd*	-1.17	-1.55	*nd*	-0.34	-3.74	-0.66	-0.60	-1.78

nd = no data

Formula (from EPA Manual): kb=(k0)(PV)(dO2)(C)(0.01)/BDsoil

kb = mg TPH/kg soil/day
k0 = % O2/day
PV = ml gas/cc soil (0.24)
dO2 = mg O2/l (1300)
C = mg hexane/mg O2 (0.29)
BD soil = g/cc soil (1.44)

TPH/kg/d), estimated using the method of EPA (1995). Calculated baseline degradation rates averaged 4.2 mg TPH/kg soil/day, a rather high value. It is evident that the potential for high contaminant degradation rates is present at the DOSB, even after relatively brief aeration. Especially high rates of oxygen consumption were observed at DOB-BV1, located in a part of the site reported to have contained the most heavily petroleum-contaminated soils (WSRC, 1994). Furthermore, the rates shown may actually represent an underestimation of the actual degradative potential. Examination of the ratio of oxygen to a helium tracer (Table 4) show a fairly rapid loss of the inert tracer from the soil gas. Thus, there appears to have been considerable exchange with surface air during the period of the test, leading to an underestimation of oxygen consumption. Influence by surface air is not entirely unexpected due to the shallow depth of the piezometers (five feet). Although baseline rates of oxygen consumption were quite high, the average rate underwent little increase as a result of injection of air or air plus TEP, and decreased (on average) during subsequent injections. It is possible that the injection of air for three days prior to the baseline test was sufficient to stimulate the microbial community, and that oxygen consumption during this test may therefore not represent a true baseline. This would explain the similarity between results of the baseline test and that following air injection. Similarity between results of air injection and air plus TEP injection could indicate either that phosphorus enrichment is not required, or that during TEP injection the system was becoming carbon limited due to a decline in contaminant levels. The latter interpretation is supported by the observation (Table 3) that TEP did stimulate respiration at DOB-BV7, located in an area with high VOC content (as shown in Fig. 11 and 12 as well as Appendix 2). Reduced contaminant levels would also explain the decline in oxygen consumption (to levels below those seen with air alone) during nitrous oxide and methane injections.

Volatile organics in gas samples. Changes in levels of tetrachloroethylene and its degradation products trichloroethylene, 1,1 dichloroethylene, and cis-dichloroethylene, as well as carbon tetrachloride, chloroform, and trichloroacetate are shown in Fig. 11 and 12 (PCE and TCE results) and Appendix 2 (all results). It was concluded that early results indicating the presence of substantial amounts (frequently > 1 ppm) of vinyl chloride actually represented a freon compound and these data are not included in the results. Indeed, analyses of Interim Action and Phase IV soil samples indicate very low levels of vinyl chloride at the DOSB (G. Rucker, personal communication). Although gas samples were taken both before and after turning off the air supply, only data collected with the system turned off are plotted. This provides a better comparison with baseline (pre-injection) data, and eliminates the possibility of artifacts due to differences in air flow to the piezometers during sample collection.

Table 4. Oxygen/helium ratios during in situ respirometry

		Piezometer								
Campaign	Time, h	1	2	3	4	5	6	7	8	9
Air	0.00	25	*nd*	39	120	*nd*	*nd*	30	*nd*	25
	0.05	25	*nd*	30	194	*nd*	*nd*	33	*nd*	25
	4.00	26	*nd*	38	342	*nd*	*nd*	38	*nd*	29
	19.50	23	*nd*	39	121	*nd*	*nd*	39	*nd*	30
	27.00	3	*nd*	41	62	*nd*	*nd*	47	*nd*	35
Air/TEP	0.00	27	*nd*	29	*nd*	*nd*	*nHe*	30	*nd*	28
	3.42	23	*nd*	30	*nd*	*nd*	*nHe*	29	*nd*	30
	18.50	17	*nd*	34	*nd*	*nd*	*nHe*	30	*nd*	36
	26.25	8	*nd*	35	*nd*	*nd*	*nHe*	22	*nd*	38
Air/N2O	0.00	25	*nd*	27	*nd*	*nd*	*nd*	34	*nd*	22
	4.25	28	*nd*	30	*nd*	*nd*	*nd*	48	*nd*	27
	21.22	28	*nd*	40	*nd*	*nd*	*nd*	49	*nd*	33
	27.82	28	*nd*	44	*nd*	*nd*	*nd*	59	*nd*	39
Air/CH4	0.00	25	*nd*	26	*nHe*	*nd*	*nHe*	35	585	21
	3.78	28	*nd*	26	625	*nd*	*nHe*	43	116	24
	21.00	27	*nd*	35	180	*nd*	*nHe*	56	535	30
	26.92	28	*nd*	36	202	*nd*	*nHe*	57	530	34

nd = no data
nHe = Helium not detected

Figure 11. Effect of injection campaigns on tetrachloroethylene (PCE) levels in soil gas.

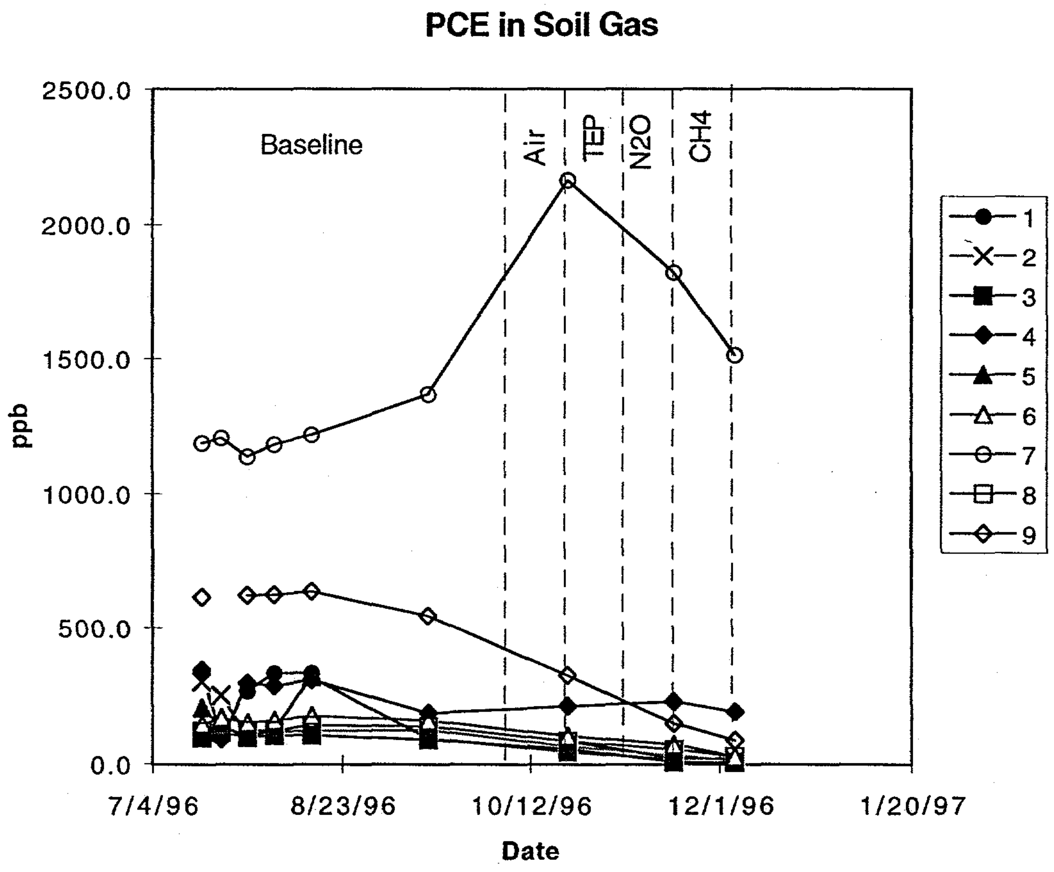
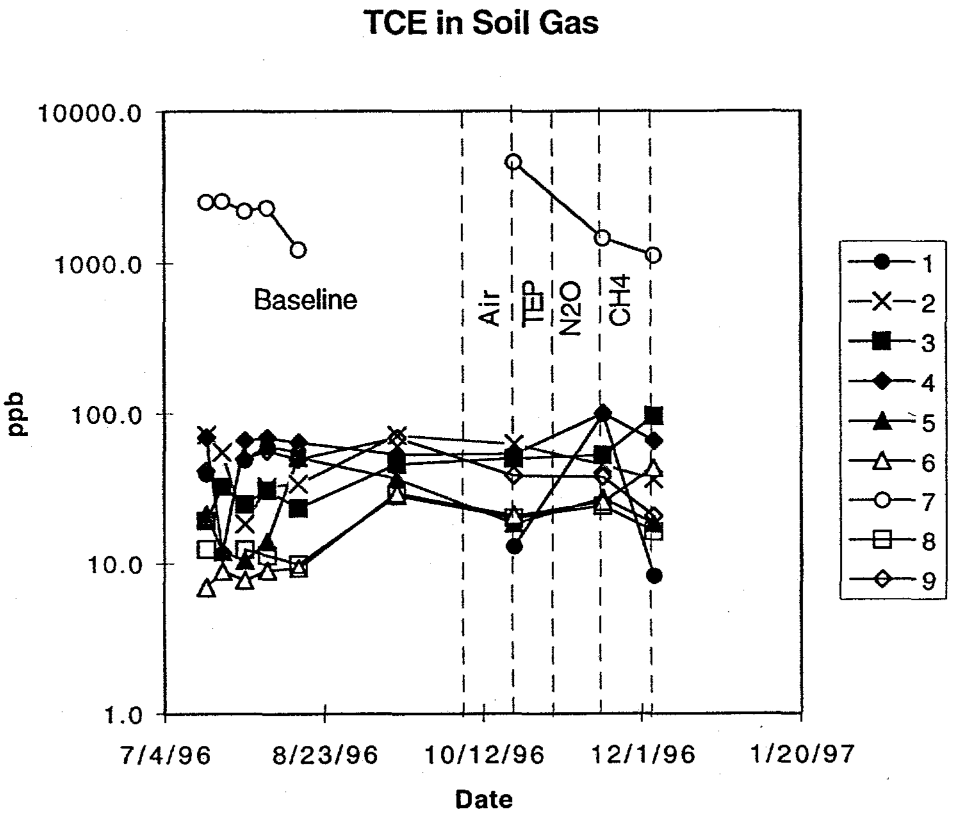


Figure 12. Effect of injection campaigns on trichloroethylene (TCE) levels in soil gas



The most clear-cut results are seen in the case of tetrachloroethylene (Fig. 11). At most piezometers, slight declines in PCE levels were seen near the end of baseline measurements, but the rate of decline increased as a result of air injection. Nutrient addition appeared to have relatively little effect on the rate of PCE degradation, except at the location with the highest PCE levels (DOB-BV7). Here PCE levels increased prior to and during air injection, but declined during subsequent measurements. Since oxygen/carbon dioxide levels at this piezometer were lowest and respiration rate was highest after TEP injection, it appears likely that PCE degradation was stimulated by phosphate enrichment, and that sufficient phosphate was introduced to allow continued microbial activity during subsequent injection campaigns. It is possible that the effect of phosphate enrichment was masked by carbon limitation at the remaining piezometers, which all had lower PCE levels. Based on linear regression analysis of data collected during air and air/nutrient injection, a mean PCE degradation rate of 1.7 ppb/day was calculated (DOB-BV7 was excluded from this estimate due to its atypically high contaminant levels). If average quantities of individual VOC's (Appendix 2) remaining in soil gas at the end of the study are summed, an estimated average VOC content of 211 ppb is obtained (vinyl chloride levels are assumed negligible, in accordance with preliminary soil analysis results). This would yield an approximate minimum cleanup time of 124 days (4 months).

There was a slight increase in PCE degradation rates at DOB-BV4, 6, 7, and 8 during methane injection. This might indicate that the addition of this carbon source stimulated the development of methanotrophic bacteria capable of carrying out a cometabolic degradation of chlorinated solvents. Methane supplementation, however, was relatively brief and it is possible that more pronounced effects would have been evident after more prolonged injection.

TCE levels at DOB-BV7 also decreased as a result of nutrient injection, but the only other substantial net decreases in TCE content during the study were seen at DOB-BV1 and 9. It is suggestive that these were all in well-aerated locations, in which microbial populations could be expected to carry out a complete degradation of PCE. At poorly aerated locations, an anaerobic pathway (PCE $\rightarrow$ TCE $\rightarrow$ DCE $\rightarrow$ VC) might predominate, particularly in the intervals between injection campaigns. Hence a lack of decline, and in some cases, a buildup of TCE and other intermediates might occur. This idea is supported by the fact that 1,1-DCE levels fluctuated erratically at most piezometers (Appendix 2).

Surface emissions. Prior to commencement of the study, projected VOC emissions from the soil surface were calculated to be negligible. This was verified by actual measurements using a B & K infrared photoacoustic analyzer and flux chamber. Raw data are shown in Appendix 3.

Values for PCE, TCE, vinyl chloride, and diesel range hydrocarbons showed little change whether or not the injection system was operating. Similar values were seen when the instrument was not connected to the flux chamber (sampling atmosphere). It therefore appears that the readings are within the noise range and surface emissions are indeed negligible. In the absence of detectable emissions, an emission rate was not calculated.

Groundwater measurements

Dissolved nutrients. Two of the most commonly limiting nutrients for microbial growth are nitrogen and phosphorus. Analyses of nutrient levels in groundwater samples from monitoring wells immediately surrounding the DOSB (see Fig. 5 for well locations) show that, while substantial amounts of nitrate are present in all wells, phosphate is in most cases undetectable (Table 5). This supports the idea that, in the presence of adequate oxygen and carbon, microbial metabolism could be phosphate-limited at the site. However, as suggested previously, the addition of phosphate might have little effect on bacterial activity once carbon becomes limiting. Chloride concentrations were highest in the closest downgradient or sidegradient wells to the solvent contamination, i.e. DOB-2, 11, 13, 14. All the wells except DOB-3 had chloride concentrations above normal background for SRS, indicating that DOB-3 may be the only well not currently or formerly contaminated. This would suggest that a large amount of natural biodegradation of solvent has already taken place, since chloride is produced as an end product of the biodegradation of chlorinated solvents. This is similar to findings in M-Area and the SRS Sanitary Landfill.

Sulfate levels are substantially higher in downgradient wells DOB-11 and 14. This likely indicates the presence (and degradation of) petroleum hydrocarbons in these locations.

Water quality parameters. Temperature, dissolved oxygen, pH, redox potential, and conductivity were measured in monitoring wells during the baseline period and following each injection campaign. Data are shown in Table 6. It is apparent that the downgradient wells DOB- 11, 13, and 14 contained less dissolved oxygen than did the remaining wells, suggesting that the presence of contaminants has stimulated microbial metabolic activity. DOB-11 (screen depth 18.7 - 23.7') and 14 (screen depth 11.7 - 16.7') had less oxygen than DOB-13 (screen depth 18.5 - 23.5'). Together with the sulfate data, this suggests that the plume of readily oxidized substrates, (e.g. petroleum hydrocarbons) does not extend to as great a depth in the vicinity of the latter two wells. DOB-11, located well within the plume, also had the lowest redox potential (consistent with its low oxygen levels). DOB-11 and 14 gave consistently higher conductivity readings , indicating the presence of more dissolved materials.

Table 5. Nutrient levels in groundwater.

			ppm				
Well	Date	Injection	Chloride	Nitrite	Nitrate	Phosphate	Sulfate
DOB 2	7/19/96	OFF	5.203	bdl	2.293	bdl	11.125
DOB 2	7/24/96	OFF	4.401	bdl	2.664	bdl	7.331
DOB 2	9/20/96	OFF	2.228	bdl	2.442	bdl	5.835
DOB 2	10/9/96	AIR	2.748	bdl	2.983	0.069	6.813
DOB 2	10/31/96	AIR/TEP	2.874	bdl	1.992	bdl	3.733
DOB 2	11/15/96	AIR/N2O	3.418	bdl	3.205	0.393	5.739
DOB 2	11/27/96	AIR/CH4	3.751	bdl	3.139	0.334	5.907
DOB 3	7/19/96	OFF	0.990	bdl	2.960	0.352	3.856
DOB 3	7/24/96	OFF	0.905	bdl	3.064	bdl	4.176
DOB 3	9/20/96	OFF	1.365	bdl	3.594	bdl	3.260
DOB 3	10/9/96	AIR	1.703	bdl	4.077	bdl	4.077
DOB 3	10/31/96	AIR/TEP	1.330	bdl	2.446	bdl	2.502
DOB 3	11/15/96	AIR/N2O	1.683	bdl	3.582	bdl	3.566
DOB 3	11/27/96	AIR/CH4	2.444	bdl	3.567	bdl	3.621
DOB 4	7/12/96	OFF	2.013	bdl	2.832	bdl	27.374
DOB 4	7/19/96	OFF	4.307	bdl	4.115	bdl	4.756
DOB 4	7/24/96	OFF	4.213	bdl	4.155	bdl	4.737
DOB 4	9/20/96	OFF	3.580	bdl	3.476	bdl	4.088
DOB 4	10/9/96	AIR	3.590	bdl	4.576	bdl	4.931
DOB 4	10/31/96	AIR/TEP	3.864	bdl	2.552	bdl	2.473
DOB 4	11/15/96	AIR/N2O	3.007	bdl	4.147	bdl	4.125
DOB 4	11/27/96	AIR/CH4	4.223	bdl	4.162	bdl	4.158
DOB 5	7/12/96	OFF	2.711	bdl	3.267	bdl	9.548
DOB 5	7/19/96	OFF	2.973	bdl	3.402	bdl	7.918
DOB 5	7/24/96	OFF	3.225	bdl	3.613	bdl	6.720
DOB 5	9/20/96	OFF	3.499	bdl	3.553	bdl	4.723
DOB 5	10/9/96	AIR	0.668	0.372	0.682	bdl	9.534
DOB 5	10/31/96	AIR/TEP	4.329	bdl	2.401	bdl	2.441
DOB 5	11/15/96	AIR/N2O	3.142	bdl	4.140	bdl	4.009
DOB 5	11/27/96	AIR/CH4	4.383	bdl	4.355	bdl	3.255
DOB 11	7/19/96	OFF	1.890	bdl	2.730	bdl	26.909
DOB 11	7/24/96	OFF	2.144	bdl	3.325	bdl	26.436
DOB 11	9/20/96	OFF	2.636	bdl	1.165	bdl	18.326
DOB 11	10/9/96	AIR	2.102	5.171	0.831	bdl	18.667
DOB 11	10/31/96	AIR/TEP	2.640	bdl	1.165	bdl	8.985
DOB 11	11/15/96	AIR/N2O	2.242	bdl	0.636	bdl	15.435
DOB 11	11/27/96	AIR/CH4	3.106	bdl	0.358	bdl	14.848
DOB 13	7/12/96	OFF	4.023	bdl	3.489	bdl	7.283
DOB 13	7/19/96	OFF	4.245	bdl	3.498	bdl	7.196
DOB 13	7/24/96	OFF	4.103	bdl	3.622	bdl	6.802
DOB 13	9/20/96	OFF	3.308	bdl	2.878	bdl	7.514
DOB 13	10/9/96	AIR	3.678	bdl	3.769	bdl	8.605
DOB 13	10/31/96	AIR/TEP	4.900	bdl	2.453	bdl	4.183
DOB 13	11/15/96	AIR/N2O	3.015	bdl	3.404	bdl	7.207
DOB 13	11/27/96	AIR/CH4	3.775	bdl	3.833	bdl	6.786
DOB 14	7/19/96	OFF	3.039	bdl	0.845	bdl	24.310
DOB 14	7/24/96	OFF	3.413	bdl	0.844	bdl	23.851
DOB 14	9/20/96	OFF	3.100	bdl	1.128	bdl	23.498
DOB 14	10/9/96	AIR	3.414	bdl	1.628	bdl	24.129
DOB 14	10/31/96	AIR/TEP	3.607	bdl	1.558	bdl	10.369
DOB 14	11/15/96	AIR/N2O	2.793	bdl	1.882	bdl	21.853
DOB 14	11/27/96	AIR/CH4	3.103	bdl	1.664	bdl	22.728

Table 6. Water quality data.

Well	Date	Status	Campaign	Temp, oC	DO, mg/l	DO, % Sat	pH	Eh, mV	Cond.	Notes
DOB2	7/19/96	OFF	Baseline	21.95	4.29	49.2	5.35	350	0.0582	
DOB2	7/24/96	OFF	Baseline	19.26	4.78	52.4	4.71	320	0.0479	
DOB2	9/20/96	OFF	Baseline	19.43	4.71	51.9	4.69	306	0.0328	
DOB2	10/9/96	ON	Air	19.57	4.68	51.8	4.61	408	0.0339	
DOB2	10/31/96	ON	Air + TEP	19.95	4.45	48.9	4.48	443	0.0362	
DOB2	11/15/96	ON	Air + N2O	19.24	5.41	59.5	4.59	428	0.0373	
DOB2	11/27/96	ON	Air + CH4							malfunction
DOB3	7/19/96	OFF	Baseline	27.97	7.15	91.8	5.81	360	0.0313	
DOB3	7/24/96	OFF	Baseline	22.57	7.37	86.1	5.33	392	0.0283	
DOB3	9/20/96	OFF	Baseline	23.25	6.96	82.7	5.13	468	0.0272	
DOB3	10/9/96	ON	Air	22.98	7.08	83.2	5.17	415	0.0281	
DOB3	10/31/96	ON	Air + TEP	22.42	6.72	77.4	5.24	409	0.0289	
DOB3	11/15/96	ON	Air + N2O	20.85	10.05	115.4	5.29	392	0.0305	going dry
DOB3	11/27/96	ON	Air + CH4	20.71	9.98	112.1	4.99	445	0.0327	going dry
DOB4	7/12/96	OFF	Baseline		8.59		5.07	311	0.056	
DOB4	7/19/96	OFF	Baseline	19.92	5.07	55.8	5.4	372	0.0471	
DOB4	7/24/96	OFF	Baseline	20.29	5.23	58.5	4.86	413	0.0476	
DOB4	9/20/96	OFF	Baseline	21.33	4.84	55.3	4.68	486	0.0383	
DOB4	9/26/96	OFF	Baseline	21.53	4.99	57.4	4.72	441	0.043	
DOB4	10/9/96	ON	Air	21.49	5.11	58.5	4.61	496	0.0383	
DOB4	10/31/96	ON	Air + TEP	21.56	5.19	58.5	4.63	430	0.0391	
DOB4	11/15/96	ON	Air + N2O	20.78	6.18	70.2	4.75	454	0.0395	
DOB4	11/27/96	ON	Air + CH4	21.01	5.29	60.1	4.54	476	0.04	
DOB5	7/19/96	OFF	Baseline	21.07	4.59	52.2	5.53	383	0.0525	
DOB5	7/24/96	OFF	Baseline	21.6	4.66	53.5	4.92	386	0.051	
DOB5	9/20/96	OFF	Baseline	21:54	3.97	45.7	4.93	435	0.0435	
DOB5	9/26/96	OFF	Baseline	22.81	4.1	48.4	5.05	408	0.0509	
DOB5	10/1/96	ON	In situ resp. I	21.86	5.9	67.4	4.83	413	0.037	
DOB5	10/4/96	ON	In situ resp. I	22.02	5.7	65.5	4.88	407	0.0362	
DOB5	10/9/96	ON	Air	22.05	5.64	65	4.84	455	0.0263	
DOB5	10/31/96	ON	Air + TEP	21.98	4.07	46.5	5.08	374	0.0464	
DOB5	11/15/96	ON	Air + N2O	21.19	4.61	53.1	5.2	422	0.0478	
DOB5	11/27/96	ON	Air + CH4	21.13	4.68	53.1	5.09	419	0.0474	
DOB11	7/12/96	OFF	Baseline		1.8		6.58	60	0.328	
DOB11	7/19/96	OFF	Baseline	21.07	1.14	13	7.27	171	0.327	
DOB11	7/24/96	OFF	Baseline	21.26	1.61	18.3	6.59	156	0.318	
DOB11	9/20/96	OFF	Baseline	21.7	0.66	7.4	6.49	276	0.179	
DOB11	9/26/96	OFF	Baseline	22.43	0.64	7.3	6.57	275	0.196	
DOB11	10/1/96	ON	In situ resp. I	21.5	0.63	7.2	6.51	251	0.169	
DOB11	10/4/96	ON	In situ resp. I	21.42	0.6	6.8	6.52	248	0.166	
DOB11	10/9/96	ON	Air	21.31	0.57	6.5	6.45	256	0.163	
DOB11	10/31/96	ON	Air + TEP	21.45	0.73	8.2	6.44	282	0.164	
DOB11	11/15/96	ON	Air + N2O	18.57	0.86	9.4	6.5	247	0.159	
DOB11	11/27/96	ON	Air + CH4	19.2	0.86	9.2	6.42	269	0.158	
DOB13	7/12/96	OFF	Baseline		6.9		5	439	0.055	
DOB13	7/19/96	OFF	Baseline	18.85	4.23	45.9	5.66	362	0.0525	
DOB13	7/24/96	OFF	Baseline	18.87	4.61	50.3	5.15	314	0.0517	
DOB13	9/20/96	OFF	Baseline	18.88	2.45	26.9	4.84	432	0.0455	
DOB13	9/26/96	OFF	Baseline	19.12	2.36	25.7	4.9	429	0.0512	
DOB13	10/1/96	ON	In situ resp. I	18.76	3.58	38.7	4.86	445	0.0447	
DOB13	10/4/96	ON	In situ resp. I	18.67	3.52	38	4.86	424	0.0446	
DOB13	10/9/96	ON	Air	18.72	3.56	38.6	4.81	443	0.0451	
DOB13	10/31/96	ON	Air + TEP	19.23	3.62	39.2	4.77	452	0.0475	
DOB13	11/15/96	ON	Air + N2O	17.58	4.16	44.3	4.83	428	0.0447	
DOB13	11/27/96	ON	Air + CH4	18.42	1.46	15.8	4.48	487	0.0749	
DOB14	7/19/96	OFF	Baseline	19.27	1.13	12.1	5.28	359	0.0806	
DOB14	7/24/96	OFF	Baseline	19.23	1.77	19.4	4.78	322	0.0813	
DOB14	9/20/96	OFF	Baseline	19.48	0.87	9.5	4.54	421	0.0706	
DOB14	9/26/96	OFF	Baseline	19.88	0.94	10.3	4.6	420	0.079	
DOB14	10/1/96	ON	In situ resp. I	19.41	0.66	7.4	4.53	448	0.0692	
DOB14	10/4/96	ON	In situ resp. I	19.31	0.83	9.1	4.53	430	0.0683	
DOB14	10/9/96	ON	Air	19.35	0.74	8	4.52	447	0.0678	
DOB14	10/31/96	ON	Air + TEP	19.51	0.86	9.3	4.5	465	0.0682	
DOB14	11/15/96	ON	Air + N2O	18.23	1.13	12..3	4.53	439	0.068	
DOB14	11/27/96	ON	Air + CH4	18.42	1.46	15.8	4.48	487	0.0749	

There was a tendency in DOB-11 and 14 for dissolved oxygen levels to decline during baseline measurements, reach a minimum during air injection, then rise during subsequent campaigns. This is consistent with the idea that microbial metabolic activity (contaminant degradation) was significantly stimulated by air injection. The progressively lesser degree of stimulation by air plus the various nutrients suggests that limitation by a nutrient other than phosphorus, nitrogen, or methane was curtailing metabolic rates. Note the tendency for conductivity to decline with time in these wells. This suggests that aeration and the consequent increase in redox potential may have reduced the mobility of metal contaminants emanating from the basin.

There was little or no change in pH (which was relatively low in most wells) as a result of the injections. This probably relates to the relatively small influence of aeration at the groundwater monitoring points due to their distance from the horizontal wells. At the SRS Sanitary Landfill, pH increases of 1 unit or more have been observed as a result of air injection (Hazen, 1996), and it is likely that similar changes occurred in the more intensively aerated regions of the DOSB.

Volatile organics in groundwater. Analyses of groundwater samples also indicated a tendency for chlorinated solvents to decrease with time in the downgradient wells DOB 11, 13, and 14, dropping below detection limits after air injection (Table 7). Except in the case of PCE and TCE in DOB-14, the data suggest that degradation of these VOC's was already underway and that air injection had little effect. The presence of small amounts of PCE in DOB-5 suggests that this well receives some influence from the basin.

Petroleum hydrocarbons and PAH's. Table 8 show data gathered during analysis of hydrocarbons in groundwater samples. Odd-numbered compounds (other than C15) were not quantified. All wells contained substantial amounts of petroleum hydrocarbons. In the case of wells DOB 2, 3, and 5, this is almost certainly due to their shallow screen depth (Table 1). DOB-4 may also be influenced at times by a hydrocarbon film at the top of the saturated zone, or may be subject to influence from the basin because of its location. In most cases, the downgradient wells DOB-13 and 14 contained the highest total hydrocarbon levels. The amounts compounds present shifted in all wells during the study. This could relate to changes in water table level. Types of compounds present also shifted, and in the those wells expected to receive the most influence from the basin (DOB-4, 11, 13, and 14), there appears to have been a loss of higher molecular weight components during the study. In several cases, high molecular weight components disappeared after injection of air alone. This might indicate microbial breakdown of these substances.

Table 7. Volatile organic compounds in groundwater.

Well	**Date**	**Campaign**	**PCE**	**TCE**	**cis-DCE**	**Freon 13**	**Vinyl Chloride**	**Freon 12**
Blank	7/19/96	Baseline	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
	7/24/96	Baseline	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
	9/20/96	Baseline	<5.0	<5.0	<5.0	<5.0	<5.0	**2.9**
	10/31/96	TEP	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
	11/16/96	N2O	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
	11/27/96	CH4	#	<5.0	<5.0	<5.0	<5.0	<5.0
DOB 2	7/19/96	Baseline	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
	7/24/96	Baseline	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
	9/20/96	Baseline	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
	10/9/96	AIR	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
	10/31/96	TEP	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
	11/16/96	N2O	<5.0	<5.0	#	<5.0	<5.0	<5.0
	11/27/96	CH4	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
DOB 3	7/19/96	Baseline	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
	7/24/96	Baseline	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
	9/20/96	Baseline	<5.0	<5.0	<5.0	<5.0	<5.0	**5.5**
	10/9/96	AIR	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
	10/31/96	TEP	7.8#	<5.0	<5.0	<5.0	<5.0	<5.0
	11/16/96	N2O	#	7.8?	#	<5.0	<5.0	<5.0
	11/27/96	CH4	#	<5.0	<5.0	<5.0	<5.0	<5.0
DOB 4	7/19/96	Baseline	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
	7/24/96	Baseline	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
	9/20/96	Baseline	<5.0	<5.0	<5.0	<5.0	<5.0	**2.65**
	10/9/96	AIR	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
	10/31/96	TEP	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
	11/16/96	N2O	#	<5.0	<5.0	<5.0	<5.0	<5.0
	11/27/96	CH4	#	<5.0	<5.0	<5.0	<5.0	<5.0
DOB 5	7/12/96	Baseline	**5.7**	<5.0	<5.0	**>5.0#**	**>5.0#**	**>5.0**
	7/19/96	Baseline	**8**	<5.0	<5.0	<5.0	<5.0	<5.0
	7/24/96	Baseline	**5.4**	<5.0	<5.0	<5.0	<5.0	<5.0
	9/20/96	Baseline	<5.0	<5.0	<5.0	<5.0	<5.0	**2.7**
	10/9/96	AIR	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
	10/31/96	TEP	5.4	8.8#	<5.0	<5.0	<5.0	<5.0
	11/16/96	N2O	#	<5.0	<5.0	<5.0	<5.0	<5.0
	11/27/96	CH4	#	<5.0	<5.0	<5.0	<5.0	#
DOB 11	7/12/96	Baseline	**11.2**	**45.7**	**123.3#**	**>5.0#**	**62.2**	**>5.0**
	7/19/96	Baseline	**7.7**	**24.2**	**67.5**	<5.0	**8.3**	<5.0
	7/24/96	Baseline	**6**	**14.3**	**37.6**	<5.0	<5.0	<5.0
	9/20/96	Baseline	<5.0	<5.0	**9.95**	<5.0	<5.0	<5.0
	10/9/96	AIR	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
	10/31/96	TEP	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
	11/16/96	N2O	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
	11/27/96	CH4	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
DOB 13	7/12/96	Baseline	<5.0	<5.0	<5.0	**>5.0#**	**>5.0#**	**>5.0#**
	7/24/96	Baseline	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
	9/20/96	Baseline	<5.0	**8.2**	<5.0	<5.0	<5.0	**2.85**
	10/9/96	AIR	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
	10/31/96	TEP	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
	11/16/96	N2O	#	<5.0	<5.0	<5.0	<5.0	<5.0
	11/27/96	CH4	#	<5.0	<5.0	<5.0	<5.0	<5.0
DOB 14	7/19/96	Baseline	**7.6**	**9.2**	**5.7**	<5.0	<5.0	<5.0
	7/24/96	Baseline	**10.2**	**14**	**5.3**	<5.0	<5.0	<5.0
	9/20/96	Baseline	**8.55**	**16.3**	<5.0	<5.0	<5.0	<5.0
	10/9/96	AIR	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
	10/31/96	TEP	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
	11/16/96	N2O	#	<5.0	<5.0	<5.0	<5.0	<5.0
	11/27/96	CH4	#	<5.0	<5.0	<5.0	<5.0	<5.0

Note: Compounds below detection limits in all samples were: 1,2 DCB; 1,3 DCB; 1,3 DCB; 1,3,5-trimethylbenzene; 2-chlorotoluene; n-propylbenzene; bromobenzene; xylenes; ethylbenzene; chlorobenzene; toluene; benzene; carbon tetrachloride; trans-DCE; 1,1-DCE; methylene chloride; chloroform; 1,1,1-TCA

 # = does not meet qualifiers

Table 8. Hydrocarbon analyses of groundwater samples.

			ppm														
Well	Date	Campaign	UNK 6.98	UNK 9.0	UNK 15.8	C10	C12	C14	C15	C16	C18	C20	C22	C24	C26	C SUM	UNKNOWN SUM
DOB-2	9/20/96	Baseline	0.3	5.1	0.5	0.3	1.1	4.9	2.3	6.9	0.0	0.0	0.0	BDL	BDL	15.5	5.9
DOB-2	10/9/96	Air	0.2	0.7	0.2	0.2	0.8	1.2	0.2	3.5	0.0	0.0	0.0	BDL	BDL	5.9	1.1
DOB-2	10/31/96	Air/TEP	0.2	2.6	0.7	0.2	0.8	38.7	5.2	37.5	0.0	0.0	0.0	BDL	BDL	82.4	3.5
DOB-2	11/15/96	Air/N2O	0.2	3.1	0.4	0.2	1.7	3.9	2.3	2.7	0.0	0.0	0.0	BDL	BDL	10.8	3.7
DOB-2	11/27/96	Air/CH4	0.4	17.0	1.1	0.4	4.9	5.6	6.1	6.3	0.0	0.0	0.0	BDL	BDL	23.3	18.4
DOB-3	9/20/96	Baseline	0.2	6.9	1.1	0.2	0.5	17.1	5.0	6.6	0.0	0.0	0.0	BDL	BDL	29.4	8.2
DOB-3	10/9/96	Air	0.1	4.2	0.4	0.1	1.7	6.8	4.4	15.5	0.0	0.0	0.0	BDL	BDL	28.5	4.7
DOB-3	10/31/96	Air/TEP	0.2	3.7	0.4	0.2	0.8	43.7	3.2	51.0	0.0	0.0	0.0	BDL	BDL	98.9	4.3
DOB-3	11/15/96	Air/N2O	1.0	38.0	1.2	1.0	4.9	3.6	24.3	17.4	0.0	0.0	0.0	BDL	BDL	51.3	40.1
DOB-3	11/27/96	Air/CH4	0.2	3.2	0.3	0.2	0.5	3.2	2.3	2.4	0.0	0.0	0.0	BDL	BDL	8.6	3.8
DOB-4	9/20/96	Baseline	1.7	23.6	1.5	1.7	5.2	3.5	4.8	2.6	2.8	28.8	148.3	BDL	BDL	197.9	26.8
DOB-4	10/9/96	Air	0.4	4.9	0.5	0.4	1.7	0.9	0.9	2.9	0.0	0.0	0.0	BDL	BDL	6.8	5.8
DOB-4	10/31/96	Air/TEP	0.2	3.6	0.7	0.2	1.9	34.4	1.3	50.0	0.0	0.0	0.0	BDL	BDL	87.7	4.5
DOB-4	11/15/96	Air/N2O	0.8	15.2	0.9	0.8	2.6	9.9	6.7	8.0	0.0	0.0	0.0	BDL	BDL	28.0	17.0
DOB-4	11/27/96	Air/CH4	0.2	2.8	0.4	0.2	0.3	0.8	2.1	2.7	0.0	0.0	0.0	BDL	BDL	6.0	3.4
DOB-5	9/20/96	Baseline	0.2	4.3	11.4	0.2	2.2	5.6	0.1	2.0	2.0	4.3	3.3	BDL	BDL	19.7	15.9
DOB-5	10/9/96	Air	0.2	5.6	1.3	0.2	0.4	2.0	0.4	1.1	0.3	0.8	1.8	BDL	BDL	6.9	7.0
DOB-5	10/31/96	Air/TEP	0.2	4.0	3509.5	0.2	1.1	16.4	0.6	6.0	1.5	3.5	3.6	BDL	BDL	32.8	3513.7
DOB-5	11/15/96	Air/N2O	0.5	15.3	14.2	0.5	1.3	3.2	1.3	0.5	3.0	3.4	8.0	BDL	BDL	21.3	29.9
DOB-5	11/27/96	Air/CH4	0.1	5.0	7.6	0.1	1.3	0.6	0.9	0.9	0.5	0.3	0.9	BDL	BDL	5.4	12.7
DOB-11	9/20/96	Baseline	4.2	8.0		0.1	1.3	25.6	2.2	9.4	5.8	6.2	5.3			56.0	12.2
DOB-11	10/9/96	Air	0.8	6.5		0.6	2.1	0.9	0.2	10.7	12.5	2.0	4.0			33.0	7.3
DOB-11	10/31/96	Air/TEP	1.6	4.4		0.5	2.3	0.6	0.8	0.8	2.6	2.1	2.4			12.0	6.0
DOB-11	11/15/96	Air/N2O	1.5	14.4		0.3	1.2	4.8	1.2	4.4	3.7	1.9	13.2			30.6	15.9
DOB-11	11/27/96	Air/CH4	0.9	7.6		0.1	1.4	31.2	0.1	13.9	1.0	0.0	0.0			47.7	8.6
DOB-13	9/20/96	Baseline	618.2	9.3		0.4	1.1	101.5	0.5	5.3	6.7	26.1	10.1			151.7	627.5
DOB-13	10/9/96	Air	1.8	5.1		0.2	1.6	7.4	1.3	4.9	2.2	5.0	5.7			28.2	6.8
DOB-13	10/31/96	Air/TEP	23.8	4.7		0.1	0.7	1.5	0.3	1.5	3.8	1.2	3.4			12.6	28.6
DOB-13	11/15/96	Air/N2O	352.1	5.5		0.2	0.7	2.8	1.6	4.4	0.3	0.9	5.7			16.6	357.6
DOB-13	11/27/96	Air/CH4	353.0	0.2		5.0	3.4	11.2	0.6	9.0	1.3	4.8	5.7			41.0	353.3
DOB-14	9/20/96	Baseline	19.9	7.2		15.8	0.7	180.7	0.8	17.2	1.8	0.7	1.5			219.2	27.1
DOB-14	10/9/96	Air	182.1	4.6		0.2	1.0	2.7	0.7	0.6	1.3	0.0	0.0			6.6	186.6
DOB-14	10/31/96	Air/TEP	247.7	12.5		0.1	0.5	0.4	1.1	0.9	0.6	0.0	0.0			3.6	260.3
DOB-14	11/15/96	Air/N2O	320.2	4.5		0.1	0.6	2.1	0.5	0.8	1.5	0.0	0.0			5.5	324.7
DOB-14	11/27/96	Air/CH4	10.4	3.7		0.1	0.4	12.3	1.4	12.2	1.7	0.0	0.0			28.1	14.1

bdl = below detection limits

Substantial levels of petroleum hydrocarbons still remained at the end of the study, although total levels were reduced in DOB-4, 11, 13, and 14. However, in view of the age of the DOSB, it is likely that the hydrocarbons are extremely weathered and may be relatively recalcitrant to microbial oxidation. Carbon limitation of potential VOC degraders might therefore still be a possibility.

Microbiological observations. Table 9 shows total bacterial numbers (Acridine Orange Direct Counts or AODC's), together with concentrations of aerobic bacteria culturable on a standard rich medium (1% PTYG) and a mineral medium provided with diesel fumes as a carbon source (MPN/Diesel). Total bacterial numbers were moderate, ranging from 12200 to 75,400 cells per ml groundwater. This amount of variation is relatively minor and indicates few differences between wells or injection campaigns. This may reflect the presence of some petroleum hydrocarbons in upgradient wells, which are screened above the water table. The majority of the bacteria were nonculturable. It is not unusual for most bacteria in environmental samples to resist cultivation on standard media and this does not necessarily indicate that they are nonviable. In most wells, numbers of culturable bacteria were lower at the end of the study than at the beginning, likely reflecting the exhaustion of readily oxidizable substrates. A relatively large number of the culturable bacteria grew on minimal medium in the presence of petroleum hydrocarbons (diesel fumes). However, the identification of these bacteria as diesel degraders is questionable, as shown by the observation that control samples inoculated onto minimal medium (no carbon source) in the absence of diesel fumes developed similar numbers of colonies (Table 9). It is likely that sufficient carbon to support growth was present in the water samples used to inoculate the plates, and hence that the diesel fumes were not the only carbon source.

Table 9. Microbiological enumerations in groundwater (cells/ml).

WELL	CAMPAIGN	DATE	AODC'S	1% PTYG	MPN/DIESEL
DOB 2	Baseline	9/26/96	1.00E+05	450	115
DOB 2	Air	10/9/96	3.11E+04	165	40
DOB 2	Air/TEP	10/31/96	7.43E+04	510	0
DOB 2	Air/N2O	11/15/96	7.03E+04	45	30
DOB 2	Air/CH4	11/27/96	5.96E+04	105	45
DOB 3	Baseline	9/26/96	5.29E+05	5700	1715
DOB 3	Air	10/9/96	2.79E+04	1505	155
DOB 3	Air/TEP	10/31/96	1.16E+05	670	50
DOB 3	Air/N2O	11/15/96	1.25E+05	495	125
DOB 3	Air/CH4	11/27/96	6.54E+04	1120	920
DOB 4	Baseline	9/26/96	1.22E+04	245	110
DOB 4	Air	10/9/96	7.76E+04	255	45
DOB 4	Air/TEP	10/31/96	1.27E+04	185	0
DOB 4	Air/N2O	11/15/96	1.51E+04	35	0
DOB 4	Air/CH4	11/27/96	1.81E+04	65	10
DOB 5	Baseline	9/26/96	9.64E+04	1450	1265
DOB 5	Air	10/9/96	4.84E+04	2450	890
DOB 5	Air/TEP	10/31/96	5.38E+04	2940	705
DOB 5	Air/N2O	11/15/96	4.58E+05	2085	945
DOB 5	Air/CH4	11/27/96	1.57E+05	1555	590
DOB 11	Baseline	9/26/96	4.69E+05	3225	730
DOB 11	Air	10/9/96	3.11E+05	2300	340
DOB 11	Air/TEP	10/31/96	2.96E+05	2905	10
DOB 11	Air/N2O	11/15/96	3.98E+05	670	85
DOB 11	Air/CH4	11/27/96	7.54E+05	535	265
DOB 13	Baseline	9/26/96	1.58E+05	2035	1800
DOB 13	Air	10/9/96	1.84E+04	1415	355
DOB 13	Air/TEP	10/31/96	1.26E+05	1130	0
DOB 13	Air/N2O	11/15/96	4.79E+04	1730	1325
DOB 13	Air/CH4	11/27/96	1.82E+05	230	45
DOB 14	Baseline	9/26/96	1.62E+05	6100	4850
DOB 14	Air	10/9/96	2.00E+05	560	1345
DOB 14	Air/TEP	10/31/96	5.60E+04	935	35
DOB 14	Air/N2O	11/15/96	9.31E+04	565	320
DOB 14	Air/CH4	11/27/96	7.35E+04	920	950

CONTROL SAMPLES

WELL	DATE	MPN/DIESEL	MPN/no C
DOB 5B	11/15/96	945	1335
DOB 11B	11/27/96	265	230
DOB 13B	11/27/96	45	125
DOB 14B	11/27/96	950	1545

Conclusions

1. Oxygen, carbon dioxide, and methane levels in soil gas, as well as a decline in PCE levels, indicate substantial levels of baseline or natural microbial activity.

2. Groundwater monitoring also indicates that a significant amount of natural contaminant biodegradation occurred prior to air injection. This is evidenced by elevated chloride and sulfate levels (resulting from degradation of chlorinated compounds and petroleum hydrocarbons, respectively), low oxygen levels, and an observed decline in volatile organic content.

3. Effective aeration was consistently achieved only at the four corner piezometers. This impaired aerobic degradation of chlorinated VOC's in the center and allowed continued anaerobic degradation (which would eventually lead to the production of vinyl chloride), as shown by the presence of intermediates in the anaerobic degradative pathway.

4. Air injection accelerated the degradation of PCE in the soil of the basin. A mean PCE degradation rate of 1.7 ppb/day was calculated for areas having low to medium PCE levels (the major portion of the site). TCE degradation was also stimulated in areas receiving adequate aeration.

5. Based on observed PCE degradation rates, minimum cleanup time is estimated at 124 days (approximately 4 months). This rate is dependent on the achievement of adequate air flow throughout the site.

6. Air injection had little or no effect on groundwater water quality parameters. This is attributed to the previous degradation of contaminants (carbon limitation), as shown by the absence of measurable VOC's .

7. Addition of TEP (triethylphosphate) resulted in a decline in oxygen levels in soil gas, and may have stimulated respiration rates and PCE degradation in portions of the site with the highest chlorinated solvent levels.

8. Aerated portions of the basin with lower initial contaminant levels showed indications of developing carbon limitation during the study. This was shown by a failure of TEP injection to stimulate respiration at these piezometers and a decline in respiration rates during subsequent injection campaigns.

9. Results of in situ respirometry indicated mean oxygen consumption levels of 0.28 % O_2/h after injection of air or air plus TEP. This results in estimated mean petroleum hydrocarbon degradation rates of about 4.2 mg/kg soil/day, a fairly high value for soils. By the end of the study, mean respiration rate was 0.12 % O_2/h, corresponding to 1.8 mg/kg soil/day.

10. Surface emissions of VOC's were negligible, even during air injection. This indicates that VOC degradation resulted primarily from biological activity rather than air stripping.

11. The induction of aerobic conditions may have reduced the mobility of metal contaminants leaching from the DOSB.

Recommendations

1. Additional aeration of the site is recommended in order to allow continued contaminant degradation.

2. Air flow to the central areas of the site is extremely restricted. It is recommended that additional injection wells be installed in regions of inadequate air flow.

3. In view of evidence suggesting that phosphorus is limiting at times in portions of the site, continued use of TEP (as needed) is suggested.

4. If time is not a primary driver, and since groundwater contamination has already decreased to below detection limits, intrinsic bioremediation could be an appropriate strategy for this site.

5. Methane injection will be necessary if PAH's, TCE, and PCE persist in the soil after a reasonable period of bioventing.

6. Recommended air flow rate is approximately 100 scfm. This is estimated to allow an minimum average 15-foot radius of influence for each of the two horizontal wells (as the system is currently configured) and an minimum affected soil volume of 5.4 X 10^5 ft^3.

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Appendix 1. Soil Gas Observations

Piezometer	Status	Campaign	Date	Time	% CH_4	% CO_2	% O_2	Pressure, "H2O	O2/CO2
1	OFF	Baseline	7/8/96	-	2.1	25.1	4	-	0.16
1	OFF	Baseline	7/18/96	-	3.1	32.1	0.1	0	0.00
1	OFF	Baseline	7/23/96	-	3.2	33.3	0.1	0	0.00
1	OFF	Baseline	7/30/96	-	3.3	33.7	0.1	0	0.00
1	OFF	Baseline	8/6/96	-	3.2	33.5	0.1	0	0.00
1	OFF	Baseline	8/16/96	-	3.8	30.5	0.7	-	0.02
1	OFF	Baseline	8/21/96	-	2.6	31.3	0	0	0.00
1	OFF	Baseline	9/19/96	-	0.8	22.8	3.8	-	0.17
1	OFF	Baseline	9/21/96	-	0.6	18.4	6.7	0	0.36
1	ON	Air	10/6/96	935	0	1.1	18.3	0.9	16.64
1	ON	Air	10/8/96	1148	0	1.1	18.3	1.6	16.64
1	ON	Air	10/9/96	1145	0	1.1	18.4	1.5	16.73
1	ON	Air	10/10/96	1237	-	0.6	18.7	-	31.17
1	ON	Air + TEP	10/24/96	938	0	1.3	18.7	0.9	14.38
1	ON	Air + TEP	10/30/96	944	0	1.3	18.6	0.8	14.31
1	ON	Air + TEP	10/31/96	1107	0	1	18.4	-	18.40
1	ON	Air + TEP	10/31/96	1330	0	1	18.2	-	18.20
1	ON	Air + N2O	11/12/96	927	0	1	19.5	-	19.50
1	ON	Air + N2O	11/15/96	1140	0	1	19	-	19.00
1	ON	Air + CH4	11/24/96	1155	0	1	19.2	0.7	19.20
1	ON	Air + CH4	11/24/96	1455	0	0.8	19.1	-	23.88
1	ON	Air + CH4	11/27/96	1217	0.8	0.9	18.6	-	20.67
2	OFF	Baseline	7/8/96	-	0	10.7	10.2	-	0.95
2	OFF	Baseline	7/18/96	-	0.3	22.3	0.4	0	0.02
2	OFF	Baseline	7/23/96	-	0	22.2	0.5	0.1	0.02
2	OFF	Baseline	7/30/96	-	5.3	4.1	0.7	0.2	0.17
2	OFF	Baseline	8/6/96	-	0.1	23	0.2	0	0.01
2	OFF	Baseline	8/16/96	-	9.5	12.6	0.6	-	0.05
2	OFF	Baseline	8/21/96	-	0	22	0	0	0.00
2	OFF	Baseline	9/19/96	-	0	12.4	7.1	-	0.57
2	OFF	Baseline	9/21/96	-	0	10.6	9.2	0	0.87
2	ON	Air	10/6/96	935	0	10.6	9.1	0	0.86
2	ON	Air	10/8/96	1148	0	9.6	10	0.1	1.04
2	ON	Air	10/9/96	1145	0	12.2	6.9	0	0.57
2	ON	Air	10/10/96	1237	-	11.2	6.6	-	0.59
2	ON	Air + TEP	10/24/96	923	0.1	17.4	0.7	0	0.04
2	ON	Air + TEP	10/30/96	1006	0	6.3	6.6	0	1.05
2	ON	Air + TEP	10/31/96	1052	0	15.9	1.5	-	0.09
2	ON	Air + TEP	10/31/96	1318	0	16.1	1.3	-	0.08
2	ON	Air + N2O	11/12/96	912	0	12.9	4.3	-	0.33
2	ON	Air + N2O	11/15/96	1132	0	12.4	4.6	-	0.37
2	ON	Air + CH4	11/24/96	1146	0	12.2	3.5	0	0.29
2	ON	Air + CH4	11/24/96	1445	0	12.2	3.8	-	0.31
2	ON	Air + CH4	11/27/96	1159	0	11.7	4.6	-	0.39

Appendix 1 (cont'd)

Piezometer	Status	Campaign	Date	Time	% CH_4	% CO_2	% O_2	Pressure, "H2O	O2/CO2
3	OFF	Baseline	7/8/96	-	0.2	14.5	7	-	0.48
3	OFF	Baseline	7/18/96	-	2.7	13.4	0	0	0.00
3	OFF	Baseline	7/23/96	-	0.4	24.1	0	0	0.00
3	OFF	Baseline	7/30/96	-	0.2	23.8	0	0.1	0.00
3	OFF	Baseline	8/6/96	-	0	23.3	0	0	0.00
3	OFF	Baseline	8/16/96	-	0.1	21.9	0	-	0.00
3	OFF	Baseline	8/21/96	-	0	22.4	0	0	0.00
3	OFF	Baseline	9/19/96	-	0	18	2.3	-	0.13
3	OFF	Baseline	9/21/96	-	0	14.6	5.5	0	0.38
3	ON	Air	10/6/96	935	0	1.8	17.7	0.5	9.83
3	ON	Air	10/8/96	1148	-	1	18.8	1	18.80
3	ON	Air	10/9/96	1145	-	1.1	18.7	0.9	17.00
3	ON	Air	10/10/96	1237	0	1.1	18.9	-	17.18
3	ON	Air + TEP	10/24/96	909	0	1.2	19.1	0.4	15.92
3	ON	Air + TEP	10/30/96	1022	0	1	19	0.4	19.00
3	ON	Air + TEP	10/31/96	1031	0	0.9	19.2	-	21.33
3	ON	Air + TEP	10/31/96	1305	0	0.9	19.1	-	21.22
3	ON	Air + N2O	11/12/96	856	0	0.4	20.3	-	50.75
3	ON	Air + N2O	11/15/96	1117	0	0.5	19.7	-	39.40
3	ON	Air + CH4	11/24/96	1137	0	0.3	20.2	0.5	67.33
3	ON	Air + CH4	11/24/96	1436	0.1	0.3	20.1	-	67.00
3	ON	Air + CH4	11/27/96	1140	0.7	0.5	19.4	-	38.80
4	OFF	Baseline	7/8/96	-	0.5	17.2	6.6	-	0.38
4	OFF	Baseline	7/18/96	-	0.5	19.9	5	0	0.25
4	OFF	Baseline	7/23/96	-	0.5	21.9	4.4	0	0.20
4	OFF	Baseline	7/30/96	-	0.4	19.6	5.1	0	0.26
4	OFF	Baseline	8/6/96	-	0.3	19.7	5.3	0	0.27
4	OFF	Baseline	8/16/96	-	0.4	19.6	4.9	-	0.25
4	OFF	Baseline	8/21/96	-	0.1	20.9	4	0	0.19
4	OFF	Baseline	9/19/96	-	0	12.6	8.8	-	0.70
4	OFF	Baseline	9/21/96	-	0	9.2	11.6	0	1.26
4	ON	Air	10/6/96	935	0	6.1	10.6	0.4	1.74
4	ON	Air	10/8/96	1148	0	4.9	12.4	1	2.53
4	ON	Air	10/9/96	1145	0	4.5	12.7	1	2.82
4	ON	Air	10/10/96	1237	-	3.5	13.2	-	3.77
4	ON	Air + TEP	10/24/96	943	0	11.6	4.2	0.5	0.36
4	ON	Air + TEP	10/30/96	956	0	8.2	8.2	0.4	1.00
4	ON	Air + TEP	10/31/96	1110	0	9.4	6.2	-	0.66
4	ON	Air + TEP	10/31/96	1334	0	9.2	7	-	0.76
4	ON	Air + N2O	11/12/96	930	0	7.1	9.8	-	1.38
4	ON	Air + N2O	11/15/96	1155	0	6.9	10.5	-	1.52
4	ON	Air + CH4	11/24/96	1156	0	6.8	10.1	0.4	1.49
4	ON	Air + CH4	11/24/96	1457	0	6.9	10.4	-	1.51
4	ON	Air + CH4	11/27/96	1222	0	7	10.5	-	1.50

Appendix 1 (cont'd)

Piezometer	Status	Campaign	Date	Time	% CH_4	% CO_2	% O_2	Pressure, "H2O	O2/CO2
5	OFF	Baseline	7/8/96	-	0.3	10.6	10.5	-	0.99
5	OFF	Baseline	7/18/96	-	0.6	21.6	0.4	0	0.02
5	OFF	Baseline	7/23/96	-	6.4	11	0.5	0.2	0.05
5	OFF	Baseline	8/1/96	-	0.3	22.2	0.4	0	0.02
5	OFF	Baseline	8/6/96	-	0.4	21.9	0.3	0	0.01
5	OFF	Baseline	8/16/96	-	4.9	9.5	0.5	-	0.05
5	OFF	Baseline	8/21/96	-	0.1	20.9	0.4	0	0.02
5	OFF	Baseline	9/19/96	-	0	12.7	6.6	-	0.52
5	OFF	Baseline	9/21/96	-	0	11	8.4	0	0.76
5	ON	Air	10/6/96	935	0	9.6	9.5	0	0.99
5	ON	Air	10/8/96	1148	0	9.7	9	0.1	0.93
5	ON	Air	10/9/96	1145	0	9.3	9.1	0	0.98
5	ON	Air	10/10/96	1237	-	10.6	4.2	-	0.40
5	ON	Air + TEP	10/24/96	927	0	15.2	2.2	0	0.14
5	ON	Air + TEP	10/30/96	1010	0	9.7	3.7	0	0.38
5	ON	Air + TEP	10/31/96	1056	0	14.7	2.1	-	0.14
5	ON	Air + TEP	10/31/96	1321	0	14.2	2.5	-	0.18
5	ON	Air + N2O	11/12/96	915	0	11.9	4.6	-	0.39
5	ON	Air + N2O	11/15/96	1136	0	12.1	4.7	-	0.39
5	ON	Air + CH4	11/24/96	1149	0	12.1	3.5	0	0.29
5	ON	Air + CH4	11/24/96	1448	0	12	4.1	-	0.34
5	ON	Air + CH4	11/27/96	1204	0	9.9	4.6	-	0.46
6	OFF	Baseline	7/8/96	-	0	13.5	8.3	-	0.61
6	OFF	Baseline	7/18/96	-	0.1	18.1	5.2	0.1	0.29
6	OFF	Baseline	7/23/96	-	0.2	18.8	5.2	0	0.28
6	OFF	Baseline	7/30/96	-	4	10.2	5.2	0	0.51
6	OFF	Baseline	8/6/96	-	0	18.3	5.2	0	0.28
6	OFF	Baseline	8/16/96	-	0	11.4	5.9	-	0.52
6	OFF	Baseline	8/21/96	-	0	17.2	5.6	0	0.33
6	OFF	Baseline	9/19/96	-	0	11	9.9	-	0.90
6	OFF	Baseline	9/21/96	-	0	10.8	10.1	0	0.94
6	ON	Air	10/6/96	935	0	9.9	6.5	0.4	0.66
6	ON	Air	10/8/96	1148	-	8.2	10.1	1	1.23
6	ON	Air	10/9/96	1145	-	4.8	13.2	0.9	2.75
6	ON	Air	10/10/96	1237	0	7.4	9.8	-	1.32
6	ON	Air + TEP	10/24/96	913	0	6	11.8	0.3	1.97
6	ON	Air + TEP	10/30/96	1028	0	5.7	13.4	0.2	2.35
6	ON	Air + TEP	10/31/96	1037	0	4	14.5	-	3.63
6	ON	Air + TEP	10/31/96	1309	0	4.1	14.1	-	3.44
6	ON	Air + N2O	11/12/96	904	0	3.7	16	-	4.32
6	ON	Air + N2O	11/15/96	1122	0	3.5	16	-	4.57
6	ON	Air + CH4	11/24/96	1139	0.3	3.8	15.2	0.2	4.00
6	ON	Air + CH4	11/24/96	1438	0.1	3.6	15.5	-	4.31
6	ON	Air + CH4	11/27/96	1148	0	3.7	15.6	-	4.22

Appendix 1 (cont'd)

Piezometer	Status	Campaign	Date	Time	% CH_4	% CO_2	% O_2	Pressure, "H2O	O2/CO2
7	OFF	Baseline	7/8/96	-	0	14	5	-	0.36
7	OFF	Baseline	7/18/96	-	0	16.2	3.6	0	0.22
7	OFF	Baseline	7/23/96	-	0	15.8	4.8	0	0.30
7	OFF	Baseline	7/30/96	-	0	15.4	4.7	0	0.31
7	OFF	Baseline	8/6/96	-	0	15.1	5	0	0.33
7	OFF	Baseline	8/16/96	-	0	15.3	4.7	-	0.31
7	OFF	Baseline	8/21/96	-	0	15.8	4.2	0	0.27
7	OFF	Baseline	9/19/96	-	0	9.2	9.6	-	1.04
7	OFF	Baseline	9/21/96	-	0	10	8.8	0	0.88
7	ON	Air	10/6/96	935	0	1.1	19	0.2	17.27
7	ON	Air	10/8/96	1148	0	0.9	18.6	0.6	20.67
7	ON	Air	10/9/96	1145	0	1.1	18.5	0.5	16.82
7	ON	Air	10/10/96	1237	-	0.6	19	-	31.67
7	ON	Air + TEP	10/24/96	946	0	1.6	18.7	0.2	11.69
7	ON	Air + TEP	10/30/96	955	0	1.5	18.6	0.2	12.40
7	ON	Air + TEP	10/31/96	1115	0	1.1	18.7	-	17.00
7	ON	Air + TEP	10/31/96	1338	0	1.3	18.4	-	14.15
7	ON	Air + N2O	11/12/96	934	0	1.3	19.1	-	14.69
7	ON	Air + N2O	11/15/96	1200	0	1.2	19	-	15.83
7	ON	Air + CH4	11/24/96	1159	0	1.2	19.1	0.2	15.92
7	ON	Air + CH4	11/24/96	1149	0	0.9	19.1	-	21.22
7	ON	Air + CH4	11/27/96	1225	0.5	1	18.8	-	18.80
8	OFF	Baseline	7/8/96	-	0	8.8	9.3	-	1.06
8	OFF	Baseline	7/18/96	-	0	16.9	0	0	0.00
8	OFF	Baseline	7/23/96	-	0	17.5	0	0	0.00
8	OFF	Baseline	8/1/96	-	0	18.3	0	0	0.00
8	OFF	Baseline	8/6/96	-	0	17.7	0	0	0.00
8	OFF	Baseline	8/16/96	-	11.2	10.6	0.1	-	0.01
8	OFF	Baseline	8/21/96	-	0	16.8	0.3	0	0.02
8	OFF	Baseline	9/19/96	-	0	11.8	5.7	-	0.48
8	OFF	Baseline	9/21/96	-	0	9	9.3	0	1.03
8	ON	Air	10/6/96	935	0	7.8	10.5	0	1.35
8	ON	Air	10/8/96	1148	0	6.9	11.8	0.2	1.71
8	ON	Air	10/9/96	1145	0	4.7	13.9	0.9	2.96
8	ON	Air	10/10/96	1237	-	4.9	11.3	-	2.31
8	ON	Air + TEP	10/24/96	930	0	13.6	0.8	0	0.06
8	ON	Air + TEP	10/30/96	1015	0	7.2	11.7	0	1.63
8	ON	Air + TEP	10/31/96	1100	0	12.3	2.7	-	0.22
8	ON	Air + TEP	10/31/96	1325	0	13.2	1.9	-	0.14
8	ON	Air + N2O	11/12/96	920	0	9.7	9.4	-	0.97
8	ON	Air + N2O	11/15/96	1143	0	7.3	11.1	-	1.52
8	ON	Air + CH4	11/24/96	1150	0	8.1	10.2	0	1.26
8	ON	Air + CH4	11/24/96	1450	0	8.3	10.4	-	1.25
8	ON	Air + CH4	11/27/96	1213	0	6.6	11.7	-	1.77

Appendix 1 (cont'd)

Piezometer	Status	Campaign	Date	Time	% CH_4	% CO_2	% O_2	Pressure, "H2O	O2/CO2
9	OFF	Baseline	7/8/96	-	0	7.5	9.3	-	1.24
9	OFF	Baseline	7/18/96	-	0	14	1.3	0.2	0.09
9	OFF	Baseline	7/23/96	-	2.1	9.3	1.3	0	0.14
9	OFF	Baseline	7/30/96	-	13.8	6.7	1.3	0	0.19
9	OFF	Baseline	8/6/96	-	0	15.5	1	0	0.06
9	OFF	Baseline	8/16/96	-	1.8	9.6	1.5	-	0.16
9	OFF	Baseline	8/21/96	-	0	14.9	1.5	0	0.10
9	OFF	Baseline	9/19/96	-	0	11.1	6	-	0.54
9	OFF	Baseline	9/21/96	-	0	11.3	6	0	0.53
9	ON	Air	10/6/96	935	0	1	19.7	0.4	19.70
9	ON	Air	10/8/96	1148	-	0.4	19.7	1.1	49.25
9	ON	Air	10/9/96	1145	-	0.3	19.9	0.9	66.33
9	ON	Air	10/10/96	1237	0	0.5	19.7	-	39.40
9	ON	Air + TEP	10/24/96	916	0	1	19.8	0.2	19.80
9	ON	Air + TEP	10/30/96	1031	0	1.5	19.2	0.2	12.80
9	ON	Air + TEP	10/31/96	1043	0	0.9	19.4	-	21.56
9	ON	Air + TEP	10/31/96	1313	0	0.9	19.3	-	21.44
9	ON	Air + N2O	11/12/96	908	0	0.5	20.5	-	41.00
9	ON	Air + N2O	11/15/96	1127	0	0.5	19.9	-	39.80
9	ON	Air + CH4	11/24/96	1142	0	0.4	20.3	0.4	50.75
9	ON	Air + CH4	11/24/96	1441	2.6	0.3	19.6	-	65.33
9	ON	Air + CH4	11/27/96	1154	2.5	0.5	19.1	-	38.20

Appendix 2. Volatile organics in soil gas

				ppb						
well #	Date	Status	Campaign	1,1 DCE	Cis DCE	Chloroform	TCA	CCl4	TCE	PCE
DOS-BV1	7/18/96	OFF	BASELINE	25.5	nf	nf	2.4	nf	39.2	305.8
	7/30/96	OFF	BASELINE	91.9	nf	nf	2.2	nf	49.0	267.4
	8/6/96	OFF	BASELINE	174.5	nf	nf	3.4	nf	60.1	334.6
	8/16/96	OFF	BASELINE	178.5	1395.4	nf	3.0	nf	55.1	333.9
	9/16/96	OFF	BASELINE	nf	nf	nf	nf	nf	nf	nf
	10/9/96	ON	AIR	nf	nf	14.0	12.2	16.3	40.4	146.1
	10/21/96	OFF	AIR	nf	nd	14.5	0.4	0.2	12.9	82.0
	11/15/96	ON	N2O	38.3	nd	5.1	0.1	1.2	8.3	4.2
	11/19/96	OFF	N2O	nf	nd	10.8	nf	nf	98.4	20.6
	11/27/96	ON	CH4	nf	nd	49.6	1.1	7.5	46.5	34.7
	12/5/96	OFF	CH4	nf	nd	6.1	1.0	42.2	8.2	16.3
DOS-BV2	7/17/96	OFF	BASELINE	33.6	nf	nf	nf	nf	71.6	300.8
	7/23/96	OFF	BASELINE	59.4	616.9	nf	22.8	0.5	54.7	252.3
	7/30/96	OFF	BASELINE	30.3	nf	1.6	0.4	0.3	18.2	102.6
	8/6/96	OFF	BASELINE	31.8	nf	nf	nf	0.3	32.4	119.6
	8/16/96	OFF	BASELINE	32.5	203.9	0.9	nf	0.1	33.5	122.2
	9/16/96	OFF	BASELINE	nf	nf	10.5	nf	7.6	70.6	124.2
	10/9/96	ON	AIR	nf	nf	nf	nf	0.5	5.8	15.5
	10/21/96	OFF	AIR	bdl	nd	15.4	3.4	0.5	61.9	63.0
	11/15/96	ON	N2O	13.4	nd	1.0	nf	nf	4.9	1.7
	11/19/96	OFF	N2O	21.7	nd	12.7	16.1	10.7	45.0	29.8
	11/27/96	ON	CH4	17.46	nd	75.45	1.443	10.089	77.664	31.842
	12/5/96	OFF	CH4	18.1	nd	12.7	1.9	42.4	35.9	10.9
DOS-BV3	7/17/96	OFF	BASELINE	nf	386.0	1.2	0.5	0.3	19.0	95.4
	7/23/96	OFF	BASELINE	41.9	458.8	nf	0.6	nf	32.4	113.8
	7/30/96	OFF	BASELINE	18.0	477.1	1.4	nf	0.4	24.6	97.8
	8/6/96	OFF	BASELINE	22.0	548.7	nf	nf	0.3	30.6	104.4
	8/16/96	OFF	BASELINE	42.9	530.5	nf	nf	nf	23.1	104.0
	9/16/96	OFF	BASELINE	nf	nf	14.7	nf	6.6	45.8	88.7
	10/9/96	ON	AIR	nf	nf	6.0	4.7	7.0	34.5	60.9
	10/21/96	OFF	AIR	bdl	nd	21.5	nf	0.3	49.7	54.0
	11/15/96	ON	N2O	9.9	nd	nf	nf	0.5	7.5	3.3
	11/19/96	OFF	N2O	nf	nd	6.1	12.9	11.0	52.3	7.9
	11/27/96	ON	CH4	nf	nd	62.5	1.2	8.4	62.4	43.1
	12/5/96	OFF	CH4	nf	nd	17.24	2.3	42.525	95.566	5.903

Appendix 2 (cont'd)

				ppb						
well #	Date	Status	Campaign	1,1 DCE	Cis DCE	Chloroform	TCA	CCl4	TCE	PCE
DOS-BV4	7/17/96	OFF	BASELINE	63.7	471.6	nf	0.6	0.2	69.2	346.5
	7/23/96	OFF	BASELINE	nf	nf	nf	2.6	nf	11.6	90.1
	7/30/96	OFF	BASELINE	74.5	279.3	nf	nf	0.3	65.8	296.4
	8/6/96	OFF	BASELINE	87.4	443.1	nf	nf	0.3	68.1	287.0
	8/16/96	OFF	BASELINE	nf	379.1	nf	nf	nf	63.9	308.7
	9/16/96	OFF	BASELINE	nf	nf	11.2	nf	8.3	52.8	188.4
	10/9/96	ON	AIR	nf	nf	nf	nf	0.6	12.6	16.0
	10/21/96	OFF	AIR	bdl	nd	10.1	3.7	0.2	53.2	213.0
	11/15/96	ON	N2O	22.5	nd	nf	nf	nf	119.6	224.9
	11/19/96	OFF	N2O	16.8	nd	9.2	0.6	1.9	99.0	229.2
	11/27/96	ON	CH4	17.6	nd	68.2	1.2	8.4	131.5	148.4
	12/5/96	OFF	CH4	nf	nd	12.7	1.4	42.4	64.7	191.9
DOS-BV5	7/17/96	OFF	BASELINE	32.4	nf	nf	nf	nf	21.0	205.4
	7/23/96	OFF	BASELINE	50.3	364.8	nf	2.8	0.1	11.9	141.7
	7/30/96	OFF	BASELINE	22.6	nf	1.3	0.8	0.4	10.4	95.6
	8/6/96	OFF	BASELINE	48.1	400.5	0.6	0.4	0.2	13.8	133.9
	8/16/96	OFF	BASELINE	97.8	764.5	4.1	2.3	0.4	50.8	319.1
	9/16/96	OFF	BASELINE	nf	nf	15.5	nf	9.8	36.3	92.4
	10/9/96	ON	AIR	nf	nf	5.0	2.4	4.4	29.5	46.5
	10/21/96	OFF	AIR	bdl	nd	12.1	0.5	0.2	18.1	42.0
	11/15/96	ON	N2O	nf	nd	nf	nf	nf	2.2	0.4
	11/19/96	OFF	N2O	20.2	nd	11.2	1.5	5.8	26.7	17.6
	11/27/96	ON	CH4	20.4	nd	83.6	1.5	10.1	70.0	37.6
	12/5/96	OFF	CH4	23.0	nd	11.6	1.8	42.4	18.2	21.0
DOS-BV6	7/17/96	OFF	BASELINE	24.8	nf	2.2	0.6	0.3	6.8	146.3
	7/23/96	OFF	BASELINE	62.8	nf	nf	0.5	0.1	8.7	171.9
	7/30/96	OFF	BASELINE	25.7	nf	2.5	nf	0.4	7.6	153.1
	8/6/96	OFF	BASELINE	37.0	nf	1.6	nf	0.3	8.9	162.6
	8/16/96	OFF	BASELINE	nf	nf	1.7	nf	0.2	9.2	177.6
	9/16/96	OFF	BASELINE	nf	nf	15.1	nf	7.0	28.9	159.9
	10/9/96	ON	AIR	nf	nf	nf	nf	nf	2.0	16.2
	10/21/96	OFF	AIR	nd	nd	33.3	nf	0.4	20.7	101.0
	11/15/96	ON	N2O	483.4	nd	nf	nf	nf	nf	4.4
	11/19/96	OFF	N2O	nf	nd	14.7	0.8	4.0	25.3	72.1
	11/27/96	ON	CH4	nf	nd	63.1	1.2	42.5	60.5	95.3
	12/5/96	OFF	CH4	21.7	nd	70.8	10.1	44.5	43.1	25.5

Appendix 2 (cont'd)

				ppb						
well #	**Date**	**Status**	**Campaign**	**1,1 DCE**	**Cis DCE**	**Chloroform**	**TCA**	**CCl4**	**TCE**	**PCE**
DOS-BV7	7/17/96	OFF	BASELINE	213.4	1850.5	3.1	2.9	0.3	2516.6	1186.8
	7/23/96	OFF	BASELINE	221.5	1979.6	2.6	2.9	0.2	2531.0	1207.2
	7/30/96	OFF	BASELINE	204.7	2028.2	3.1	2.2	0.4	2185.9	1138.2
	8/6/96	OFF	BASELINE	199.6	2073.3	2.6	3.1	nf	2300.4	1183.2
	8/16/96	OFF	BASELINE	nf	2551.5	nf	nf	0.3	1226.2	1218.6
	9/16/96	OFF	BASELINE	328.0	2486.2	16.0	nf	7.4	nf	1366.6
	10/9/96	ON	AIR	nf	nf	nf	nf	nf	222.5	191.6
	10/21/96	OFF	AIR	18.3	nd	15.0	3.0	0.3	4607.9	2166.0
	11/15/96	ON	N2O	75.6	nd	2.6	nf	1.7	578.5	597.7
	11/19/96	OFF	N2O	33.9	nd	15.9	0.7	3.2	1442.2	1820.0
	11/27/96	ON	CH4	27.7	nd	110.8	2.9	10.7	507.3	382.1
	12/5/96	OFF	CH4	41.872	nd	12.386	1.787	42.553	1114.705	1513.72
DOS-BV8	7/18/96	OFF	BASELINE	42.3	nf	nf	nf	nf	12.3	121.6
	7/30/96	OFF	BASELINE	55.5	nf	1.6	nf	0.3	12.2	122.6
	8/6/96	OFF	BASELINE	27.7	nf	1.8	0.3	0.2	11.1	122.8
	8/16/96	OFF	BASELINE	nf	nf	1.1	nf	0.1	9.8	142.3
	9/16/96	OFF	BASELINE	nf	nf	15.4	nf	7.7	28.0	137.9
	10/9/96	ON	AIR	nf	nf	nf	nf	nf	3.9	14.9
	10/21/96	OFF	AIR	nf	nd	18.6	0.3	0.2	19.9	83.0
	11/15/96	ON	N2O	15.8	nd	nf	nf	nf	nf	13.2
	11/19/96	OFF	N2O	nf	nd	12.1	0.5	2.2	23.9	52.7
	11/27/96	ON	CH4	22.5	nd	144.8	2.9	11.3	86.1	52.4
	12/5/96	OFF	CH4	nf	nd	9.3	1.1	42.3	16.0	26.8
DOS-BV9	7/18/96	OFF	BASELINE	81.9	nf	1.6	0.2	0.3	41.3	616.0
	7/30/96	OFF	BASELINE	79.0	nf	2.7	nf	0.5	49.1	623.0
	8/6/96	OFF	BASELINE	62.9	nf	nf	nf	0.3	55.9	625.4
	8/16/96	OFF	BASELINE	58.2	nf	1.4	nf	0.2	49.4	636.8
	9/16/96	OFF	BASELINE	nf	nf	16.7	nf	8.2	68.5	544.6
	10/9/96	ON	AIR	nf	nf	nf	nf	nf	3.4	13.1
	10/21/96	OFF	AIR	nf	nd	30.4	0.5	0.7	38.3	326.0
	11/15/96	ON	N2O	nf	nd	2.8	nf	nf	3.9	3.7
	11/19/96	OFF	N2O	31.7	nd	18.5	0.7	3.7	37.4	148.6
	11/27/96	ON	CH4	24.2	nd	69.9	1.2	9.7	66.5	66.6
	12/5/96	OFF	CH4	26.6	nd	10.8	1.2	42.3	20.5	84.7
1HW390'	9/15/96	OFF		nf	nf	nf	nf	nf	nf	nf
2HW390'	9/15/96	OFF		nf	nf	nf	nf	nf	758.3	1208.7

nd - not determined (calibration standard not available or not detectable)
nf - peak not found in sample
bdl - peak found but below detection limits

Appendix 3. Soil surface emissions

- 1302 Measurement Data ------- 1732827/2803 - 1996-12-05 14:50 - Page 1 -

1302 Settings:

Compensate for Water Vap. Interference : YES
Compensate for Cross Interference : YES
Sample Continuously : NO
Sampling Interval : 00:05
Pre-set Monitoring Period : NO
Measure
Gas A: PCE : YES
Gas B: TCE : YES
Gas C: Vinyl chloride : YES
Gas D: CO2 : YES
Gas E: Diesel : YES
Water Vapour : YES

Sampling Tube Length : 2.0 ft
Air Pressure : 983.92 mbar
Normalization Temperature : 20.0 C

General Information:

Start Time : 1996-12-04 14:02
Stop Time : 1996-12-04 16:19
Results Not Averaged
Number of Event Marks : 0
Number of Recorded Samples : 28

	Alarm Limit	Max	Mean	Min	Std.Dev
Gas A:	________	278E-03	-250E-03	-410E-03	133E-03
Gas B:	________	21.6E-03	-110E-03	-265E-03	75.2E-03
Gas C:	________	2.95E+00	2.34E+00	1.33E+00	386E-03
Gas D:	________	851E+00	649E+00	373E+00	138E+00
Gas E:	________	733E-03	590E-03	485E-03	74.6E-03
Water:		16.3E+00	13.9E+00	479E-03	3.24E+00

Appendix 3 (cont'd)

- 1302 Measurement Data ------- 1732827/2803 - 1996-12-05 14:50 - Page 2 -

Samples Measured From 1996-12-04 14:02

Samp. No.	Time hh:mm:ss	Gas A ppm	Gas B ppm	Gas C ppm	Gas D ppm	Gas E ppm	Water Tdew	
1	14:02:58	278E-03	21.6E-03	1.75E+00	378E+00	500E-03	1.96E+00	
2	14:07:55	16.0E-03	8.90E-03	1.52E+00	374E+00	510E-03	1.78E+00	Sampling
3	14:12:54	-41E-03	9.55E-03	1.33E+00	373E+00	529E-03	479E-03	atmosphere
4	14:17:54	-187E-03	18.8E-03	2.29E+00	486E+00	699E-03	11.4E+00	
5	14:22:54	-227E-03	-102E-03	2.42E+00	513E+00	733E-03	12.9E+00	
6	14:27:54	-223E-03	-177E-03	2.69E+00	539E+00	670E-03	14.1E+00	
7	14:32:54	-267E-03	-139E-03	2.65E+00	553E+00	685E-03	14.6E+00	
8	14:37:53	-342E-03	-184E-03	2.91E+00	564E+00	688E-03	14.9E+00	Flux chamber,
9	14:42:53	-357E-03	-190E-03	2.79E+00	587E+00	645E-03	14.8E+00	injection off
10	14:47:53	-349E-03	-192E-03	2.95E+00	601E+00	623E-03	15.6E+00	
11	14:52:53	-305E-03	-214E-03	2.76E+00	617E+00	612E-03	15.7E+00	
12	14:57:53	-410E-03	-111E-03	2.75E+00	629E+00	714E-03	15.7E+00	
13	15:02:53	-252E-03	-90E-03	2.23E+00	642E+00	646E-03	15.7E+00	
14	15:07:52	-258E-03	-125E-03	2.47E+00	649E+00	639E-03	16.3E+00	
15	15:12:52	-299E-03	-195E-03	2.47E+00	661E+00	642E-03	16.0E+00	
16	15:17:52	-281E-03	-79E-03	2.30E+00	687E+00	552E-03	16.3E+00	
17	15:22:52	-268E-03	-106E-03	2.19E+00	703E+00	564E-03	16.0E+00	
18	15:27:52	-261E-03	-40E-03	2.14E+00	718E+00	498E-03	15.4E+00	
19	15:32:52	-340E-03	-127E-03	2.45E+00	724E+00	529E-03	15.1E+00	
20	15:37:52	-267E-03	-62E-03	2.19E+00	740E+00	617E-03	14.8E+00	
21	15:42:51	-276E-03	-117E-03	2.13E+00	755E+00	557E-03	14.8E+00	Flux chamber,
22	15:47:51	-301E-03	-96E-03	2.27E+00	773E+00	485E-03	14.7E+00	injection on
23	15:52:51	-274E-03	-126E-03	2.21E+00	783E+00	530E-03	15.1E+00	
24	15:57:51	-321E-03	-265E-03	2.67E+00	799E+00	579E-03	14.8E+00	
25	16:02:51	-277E-03	-78E-03	2.08E+00	811E+00	509E-03	14.6E+00	
26	16:07:51	-285E-03	-134E-03	2.34E+00	826E+00	525E-03	14.2E+00	
27	16:12:51	-370E-03	-190E-03	2.69E+00	838E+00	552E-03	13.8E+00	
28	16:17:50	-253E-03	782E-06	1.97E+00	851E+00	495E-03	13.8E+00	