

# Techniques for Rapidly Evaluating the Progress of In-Situ Remediation

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*Although standard methods of monitoring the progress of in-situ remediation may provide general results for the most permeable zones affected by soil vapor extraction or bioventing, they are essentially unsuccessful at providing information on the degree of heterogeneity within the remediation zone and on the existence of "hot spots." Data are presented that suggest that monitoring the concentrations of fixed and biogenic gases and measuring soil permeability on a small-scale basis may circumvent the common problems associated with assessing the progress of in-situ remediation. The costs of these monitoring techniques are minor compared to those of designing and operating an in-situ remediation system, and may save additional time and costs by identifying problem areas early in the cleanup process.*

Confirming the in-situ remediation of organic chemicals in soil is usually accomplished by collecting samples from selected points at the termination of a designated operation period. There are two common problems associated with this procedure; one is temporal and the other is spatial in nature. First, the timing of this confirmation or validation step is usually based either on cleanup predictions that were made during the design stage or on data collected from the periodic monitoring of vapor or groundwater wells. In the case of soil vapor extraction (SVE) or bioventing operations, the concentration of volatile organic compounds (VOCs) measured in the blower exhaust of extraction wells are used to assess the performance of in-situ remediation. Second, the location and depth of confirmation samples are selected either randomly or with a bias toward the most contaminated zones (according to the results of pre-remediation studies).

It is commonly observed that, despite calculations or monitoring data to the contrary, not all soils within the treatment zone are remediated to target cleanup levels. This phenomenon is due, at least in part, to the inadequacy of conventional monitoring data for evaluating the progress of in-situ remediation. The focus of this article is on the use of fixed/biogenic gas analyses and air permeability measurements in understanding small-scale processes that occur during large-scale remediation projects such as SVE and bioreclamation. A discussion of the physical and chemical

processes underlying the use of these discrete soil vapor measurements to monitor in-situ remediation is followed by a case study illustrating their use in soil bioventing.

### BACKGROUND

The analysis of fixed and biogenic gases (e.g., carbon dioxide, oxygen, methane, nitrogen, and hydrogen sulfide) was originally introduced to circumvent a major limitation inherent in conventional soil gas surveying techniques—their inability to detect nonvolatile petroleum products and highly degradable fuels. Even though these hydrocarbon contaminants are not detectable in soil vapor (due to either their low volatility or their degradation in shallow aerobic soils), production of carbon dioxide gas from their oxidative degradation in soils consistently results in  $\text{CO}_2$  concentrations that are substantially greater than those in adjacent uncontaminated areas (Kerfoot et al., 1988; Suchomel et al., 1990; Robbins et al., 1990). Hence, contaminated regions can often be delineated by the presence of elevated  $\text{CO}_2$  levels. Similarly, petroleum contamination in more reducing environments such as groundwater aquifers (e.g., created by the presence of nonaqueous phase liquids on the water table) usually results in a methanogenic biodegradation pathway that produces locally high concentrations of methane in soil gas (Marrin, 1991).

Although the interpretation of fixed and biogenic gas ratios is related primarily to biochemical and oxidation-reduction (redox) conditions, the interpretation of contaminant removal by vapor extraction is a function of physical soil properties and of VOC partitioning dynamics. The partitioning of VOCs between the aqueous, mineral, or organic phases (e.g., comprising groundwater aquifers or soil) and the gas phase has traditionally been described by a combination of physical laws that assume that equilibrium conditions exist. Field measurements of VOC concentrations within the various soil phases suggest that, in fact, chemical equilibria do not exist and that contaminant desorption is kinetically controlled or time dependent (Beusseau et al., 1991). The physical property of permeability is often assumed to be relatively homogeneous, which is not corroborated by the high spatial variability in soil characteristics that affect this property (e.g., porosity, water content, particle size). These factors profoundly affect both the feasibility and time requirements of remediating sites by enhanced bioreclamation or SVE.

### CONVENTIONAL MONITORING TECHNIQUES

The design of bioremediation, SVE, and bioventing systems is usually based on *large-scale* or *average site* parameters such as air permeability, moisture content, organic carbon content, redox potential, and hydraulic conductivity. These parameters are obtained by the characterization of soil, groundwater, or soil vapor samples collected from a selected number of locations. Similarly, the monitoring of these in-situ remediation techniques is based on *large-scale* or *average* changes in physical or chemical properties within the remediation site, providing limited data on *small-scale* system performance. Such small-scale anomalies in the remediation

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process are important because the ultimate verification of site cleanup is performed by collecting and analyzing small volumes of soil or water from discrete locations.

### **Soil and Groundwater Bioreclamation**

Bioreclamation of contaminated soil or groundwater involves increasing the numbers of hydrocarbon-degrading microorganisms in soil by adding mineral nutrients and an appropriate electron acceptor (e.g., oxygen or nitrate), which are required for growth (Fogel et al., 1989). The microorganisms convert the organic carbon to new biomass and degradation by-products, consisting of highly water-soluble compounds (e.g., alcohols, phenols, and organic acids) as well as biogenic gases such as methane and carbon dioxide (Wolin and Miller, 1987). Although there are a variety of computer models available to project biodegradation rates and pathways on the basis of initial site parameters (Widdowson and Aellon, 1991; Rifai et al., 1988), there are fewer options for actually monitoring the progress of in-situ bioremediation. Typical monitoring techniques include measuring the gaseous or aqueous concentrations of (1) hydrocarbon or substrate concentrations, (2) intermediate degradation products, and (3) residual nutrients and electron acceptors (e.g., nitrate, oxygen, sulfate, phosphate) in groundwater, soil pore water, or soil gas.

The problem with all of these monitoring options is they provide only an indication of conditions near the extraction well or, at best, an average of soil or groundwater conditions within the capture zone of the well. Barcelona and Holm (1991) have identified the redox capacity of aquifer solids as being one of the most important factors affecting the enhanced bioremediation of groundwater. Unfortunately, subsurface redox conditions are highly nonuniform and vary spatially in response to pH, natural organic matter, concentration of substrates and electron acceptors, and water flow dynamics. Substantial intrasite differences in aquifer redox capacities and metabolic pathways of biodegradation have been described by Barcelona and Holm (1991) and Godsy et al. (1992), respectively.

Any technique that could increase the resolution of detecting such differences in soil and microbial properties would necessarily enhance the evaluation of in-situ remediation. As a consequence of this real-time monitoring, modifications could be made to the enhancement techniques and additional wells could be installed in areas that appeared to be unaffected by the original design. Furthermore, such a technique would reduce the probability that the remediation period would have to be repeatedly extended because confirmation samples contained hydrocarbon concentrations above the specified cleanup levels.

### **Soil Bioventing**

The technique of soil bioventing incorporates both the processes of soil vapor extraction and in-situ soil bioremediation. The methodology involves moving air through the soil under forced vacuum conditions (1) to remove the most volatile fraction of the contamination by partitioning into the soil gas and subsequent advective flow within the soil gas, and

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(2) to aerobically bioremediate the less volatile fraction by supplying air to the hydrocarbon-contaminated soils (Hogg et al., 1992; Dey et al., 1991). The degree to which volatile hydrocarbons can be removed by SVE is dependent on their partitioning from the organic, aqueous, or mineral fraction of the soil into the soil vapor. This process is often kinetically controlled or rate limited due to either the nonequilibrium partitioning of contaminants between soil phases or the diffusion of VOCs through soils possessing low air permeabilities (Gierke et al., 1992).

Due to the rate-limited removal of contaminants from soil and the unpredictable flow paths for subsurface air movement to a vapor extraction well, it is difficult to estimate the progress of the SVE portion of bioventing by simply measuring VOC concentrations in the blower exhaust over time. Even if the system is shut down for an extended period of time (i.e., in order to allow subsurface conditions to approach a chemical equilibrium), subsequent VOC levels in the extraction wells are only representative of average conditions within the capture zone or of conditions along the most permeable airflow pathway.

Hinchee et al. (1991) have suggested that the biodegradation portion of bioventing should include the monitoring of volatile hydrocarbons, carbon dioxide, and oxygen in the exhaust gases from both contaminated and uncontaminated locations. Monitoring the concentration of these analytes should provide information on microbial respiration, carbon conversion, oxygen supply, and soil redox conditions (Marrin et al., 1991). However, the exclusive use of bioventing extraction wells to monitor the progress of bioventing leads to similar problems discussed in the previous paragraph. Given the documented spatial variability of redox conditions, metabolic pathways, and soil air permeabilities, a better monitoring procedure would include the sampling and analysis of these gases on a small-scale or high-resolution basis so that unremediated pockets of hydrocarbon contamination could be identified prior to the confirmation phase.

#### ALTERNATIVE APPROACH TO MONITORING

An alternative approach to monitoring the progress of in-situ remediation is to focus on small-scale differences in hydrocarbon partitioning, redox conditions, and soil air permeability. If measurements of these parameters could be conducted on relatively small volumes of soil, the difficulties associated with heterogeneity and anisotropy may be reduced and, consequently, remediation techniques could be more accurately monitored.

#### Feasibility

The use of soil gas sampling techniques to estimate the phase partitioning of VOCs between soil or groundwater and soil gas has been used as a method of validating fate and transport models (Marrin 1992a). In essence, soil gas surveys are designed to quantify VOC concentrations in soil gas that approach a chemical equilibrium with other phases of the subsurface. In fact, many soil gas sampling techniques are not adequate for that purpose because of the large volumes or high flow rates associated

**Table 1.** Redox Potentials for Biochemical Reactions.

	Redox Potential (mv)	Major Biogenic Gases
Acrobic Respiration	+350	CO <sub>2</sub>
Denitrification	+200	N <sub>2</sub> , CO <sub>2</sub>
Iron reduction	+100	CO <sub>2</sub>
Sulfate reduction	-150	H <sub>2</sub> S, CO <sub>2</sub>
Methanogenesis	-250	CH <sub>4</sub>

with sample withdrawal. Based on site-specific empirical data for contaminant partitioning among soil compartments, hydrocarbon concentrations measured in soil vapor over the course of a remediation project may be used to predict the range of residual concentrations in those soils.

The importance of redox conditions in assessing both the feasibility and progress of in-situ bioremediation has been outlined previously. Due to the association between redox potential and metabolic pathways (see **Table 1**), oxygen utilization and biogenic gas production can be used to estimate the redox conditions under which hydrocarbons are degrading. For example, Marrin (1992b) has demonstrated that the ratio of carbon dioxide to methane concentrations may be used to estimate redox conditions, ranging from +350 to -400 millivolts, in shallow groundwater. The success in using these biogenic gas ratios is probably related to (1) the narrow range of conditions and metabolic pathways under which methane is produced, (2) the narrow range of redox conditions under which oxygen is consumed, (3) the wide range of conditions and metabolic pathways under which carbon dioxide is produced, and (4) the thermodynamics of methane oxidation via different electron acceptors (e.g., oxygen, nitrate, sulfate, and iron).

The air permeability of soils is a major site-specific factor in assessing whether soils are amenable to vapor extraction or to oxygen delivery in the form of airflow. There are a number of mathematical models appropriate for estimating the air permeability of soils based on flow/vacuum readings at an extraction well (or probe) and measurement of vacuum pressures at surrounding observation points (e.g., Johnson et al., 1990). Empirical data generated from small-scale permeability tests indicate that the radius of influence surrounding one-inch diameter (O.D.) extraction probes is quite limited and is relatively constant among various soil types (Marrin et al., 1991). Hence, the logistics of performing small-scale permeability tests can be simplified enough so that portable equipment and minor modifications to the permeability calculations may be used.

#### Cost

The costs associated with performing soil vapor tests as a means of

documenting the progress of in-situ remediation are similar to those of conventional monitoring techniques. The costs of sampling and analyzing soil vapor samples for VOCs and fixed/biogenic gases is approximately \$100 to \$250 per point, depending on the number of analytes selected and the desired sampling depth (normally less than twenty-five feet below ground surface [bgs]). These costs are typical of real-time soil vapor investigations and may be lower if vapor samples are submitted to an analytical laboratory instead of analyzed on-site. If gas samples must be collected from greater depths, the installation of vadose zone wells may be necessary. In addition, groundwater wells that are screened substantially above the water table may be used for purposes of soil vapor sampling; however, the screened interval should correspond to the soil units of interest.

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The costs associated with small-scale permeability testing are less standardized because there are relatively few contractors that offer this service. For example, a charge of \$250 per location (or per depth interval) has been applied to this test as part of a menu of remediation support services offered by one specialized contractor. Typical costs for performing remediation evaluations are in the range of \$8,000 to \$20,000 a year for quarterly monitoring. The exact costs will depend on the size of the remediation site, as well as the depth and type of contamination.

#### CASE HISTORY

In order to illustrate the use of soil gas data for monitoring the progress of in-situ remediation, we present a case history involving the bioventing of gasoline-contaminated soil. The project was conducted on a three-acre site in Southern California for purposes of reducing the total petroleum hydrocarbon (TPH) concentrations in soil below 1,000 mg/kg. Chemical analyses of the contaminated soil indicated the presence of fuel hydrocarbons in the approximate carbon range of  $C_6$  through  $C_{10}$  at depths ranging from ten to thirty feet bgs. The highest concentrations of TPH (4,000 to 5,000 mg/kg) were present in silty and clayey sands interbedded with coarse sands and small cobbles.

#### Procedures

Samples of soil gas were withdrawn and tested on-site on a small-scale basis.

#### Soil Gas Sampling and Air Permeability Testing

A predetermined volume of soil gas was pumped through steel sampling probes, which were driven to the sampling depth using a vehicle-mounted hydraulic hammer. Vapor samples were withdrawn using a two-stage evacuation system that permitted the measurement of airflow rates over a specified vacuum drop. Vapor samples were collected with a gas-tight syringe as soon as the evacuation system had returned to ambient pressure.

Soil air permeabilities of the soil were measured on a small-scale basis by installing one-inch-diameter probes to depths of fourteen to twenty feet

bgs. Once at the target depth, the probe was withdrawn off the tip a distance of six to twelve inches, which served as the vertical interval over which the soil gas was extracted. Soil vapor was withdrawn from the probes by connecting the aboveground end to a positive displacement blower, which induced vacuum pressures of ten to forty inches of water within the probes. Observation probes were installed to fifteen to twenty feet bgs at various distances and compass directions from the extraction probe in order to assess the sensitivity of permeability calculations to radius of influence. This technique is described in more detail by Marrin et al. (1991).

#### **Analytical Chemistry**

Gas samples were analyzed on-site using a Hewlett-Packard model 5890 gas chromatograph, which was equipped with flame ionization (GC/FID) and thermal conductivity (GC/TCD) detectors. Separation of the hydrocarbon analytes was achieved by using DB-WAX megabore capillary column (J&W Scientific) with nitrogen as the mobile phase, whereas the fixed gases were separated using a CTR-1 dual packed column (Alltech Associates) with helium as the mobile phase. Identification and quantification of the analytes were performed using external standards that were commercially prepared in the appropriate carrier gas (i.e., nitrogen or helium). All samples were analyzed for oxygen ( $O_2$ ), carbon dioxide ( $CO_2$ ), and total volatile hydrocarbons (TVH) in the range of  $C_1$  through  $C_{10}$ . As a result of their physiochemical properties (i.e., vapor pressure and octanol-water partition coefficient),  $C_{10}$  hydrocarbons present under normal soil conditions do not partition into the vapor phase at concentrations that are readily detectable in soil gas (Marrin, 1988).

#### **Remediation Monitoring via Extraction Wells**

Before designing and installing a soil bioventing system, a pilot test was conducted in order to generate data on soil permeability, radii of influence associated with extraction wells, flow/vacuum dynamics, and VOC partitioning between soil and vapor phases. The data from short-term (e.g., two to five hours) pilot tests were collected from two four-inch-diameter extraction wells, located about sixty feet apart and screened through the most contaminated soil interval at ten to thirty-five feet bgs. Results from both pilot test wells indicated that the air permeability of soils was in the range of 9.0 to 9.5 darcys ( $8.8$  to  $9.3 \times 10^{-8}$   $cm^2$ ). At flow rates designed for the full-scale remediation system, the anticipated capture zone or radius of influence for the wells was calculated to be at least forty feet.

During the course of the pilot test, samples of the blower exhaust were collected and analyzed for volatile hydrocarbons and major fixed and biogenic gases including oxygen, nitrogen, and carbon dioxide. Concentrations of both the fuel hydrocarbons ( $C_1$  to  $C_{10}$ , carbon range) and fixed and biogenic gases reached a "relative" steady state after one to three hours of vapor extraction. The concentrations of major analytes are shown in **Table 2**, suggesting that there was minimal variability in analyte concentrations between the two wells. After six months of remediation, the

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**Table 2.** Analyte Concentrations from Bioventing Extraction Wells.

Duration of Remediation (months)	Extraction Well	TVH <sup>a</sup> (ppmv)	LMWH <sup>b</sup> (ppmv)	Carbon Dioxide (%)	Oxygen (%)	Nitrogen (%)
0 <sup>c</sup>	A <sup>d</sup>	3400	80	14.3	2.8	82.6
0 <sup>c</sup>	B <sup>d</sup>	2600	10	11	6.2	82.5
6	A	160	<5	2.3	17.9	79.8
6	B	100	<5	2.2	18.6	79.2
16	A	930	<5	4.8	14.1	81.1
16	B	180	<5	4.8	13.5	81.7

<sup>a</sup> Total Volatile Hydrocarbons (carbon range of C<sub>1</sub>-C<sub>10</sub>).

<sup>b</sup> Low Molecular Weight Hydrocarbons (fraction of TVH representing C<sub>1</sub>-C<sub>4</sub> gases).

<sup>c</sup> Analyses performed during pilot test.

<sup>d</sup> Average of concentrations reported for analytes after system approached steady state.

extraction wells were shut down for a period of four days before collection and analysis of the vapor samples. At the end of sixteen months, the extraction wells remained idle for a period of three weeks before the vapor samples were collected and analyzed.

Generally, concentrations of TVH and biogenic gases (CO<sub>2</sub> and N<sub>2</sub>) in the blower exhaust decreased during the remediation period, whereas oxygen concentrations increased. These observations are consistent with the hypothesis that petroleum hydrocarbons are stripped from the soils and that airflow through the contaminated zone sweeps away the biogenic gases and maintains elevated oxygen levels. Although biodegradation rates (as measured by in-situ respirometry tests) were probably elevated, the actual concentration of biogenic gases in the vapor exhaust decreased due to the advective flow of soil gases past the contaminated soil. The most significant disparity in analyte concentrations between the wells was recorded for TVH at sixteen months, following a three-week cessation of bioventing. As will be illustrated in the following section, this difference was probably related to the presence of unremediated pockets of contamination within the capture zone of Well A, which were reflected in the vapor-phase TVH concentrations only after the system was shut down long enough to allow chemical equilibria among the soil phases to be approached.

The similarity in analyte concentrations at the two wells was probably related to (1) their close areal proximity, (2) their screening over the

identical vertical interval within the contaminated soil, and (3) minimal differences in shallow soil properties (e.g., from the ground surface to ten feet bgs) at each of the two wells. Concentrations of oxygen and carbon dioxide are similar to those reported by Marrin (1991) for petroleum-contaminated soils and is substantially beyond the range of levels normally reported for background or uncontaminated soils. Sposito (1989) has found that  $\text{CO}_2$  levels are generally less than 3 percent and oxygen concentrations greater than 10 percent in uncontaminated shallow soils.

The TVH concentrations of 3400 and 2600 ppbv are characteristic of soil vapor in contact with moderately contaminated soils, however, a comparison of these TVH levels in the blower exhaust to maximum TPH concentrations in soil suggest that hydrocarbon partitioning between the two phases is best represented by a chemical disequilibrium (i.e., measured TVH concentrations were as much as two orders of magnitude less than those calculated under the assumption of chemical equilibrium between soil and vapor phases). This apparent disequilibrium is probably a function of both hydrocarbon partitioning dynamics and the adequacy of blower exhaust samples in representing vapor-phase hydrocarbon concentrations adjacent to the most highly contaminated soil. For example, there is probably substantial mixing of the most contaminated soil gas with vapors drawn from the ground surface or from less contaminated soils within the capture zone of the extraction wells. Similarly, it is likely that airflow rates induced during the pilot test were sufficient to exceed the desorption kinetics of hydrocarbons from organic or aqueous phases of the soil to the adjacent vapor phase.

#### Remediation Monitoring with Soil Gas Probes

In addition to monitoring the progress of bioventing by sampling and analyzing the blower exhaust, soil gas probes were installed and sampled at sixteen months. **Table 3** lists the concentrations of soil gas analytes sampled from three soil gas probes within the capture zone of each extraction well. Soil gas probes were installed within the previously contaminated strata (i.e., fourteen to sixteen feet bgs) at a distance of six to eleven feet from the extraction wells. These data suggest that there are substantial differences in soil gas composition as a function of location (e.g., various compass directions from the well) within the anticipated capture zones for the bioventing wells. TVH concentrations differed by as much as 400-fold, whereas levels of fixed and biogenic gases suggested a wide range in subsurface redox conditions.

The data presented in Table 3 were collected at the same time that the extraction wells were sampled and analyzed (see sixteen-month monitoring results in Table 2). A comparison of these two tables suggests that monitoring data generated by analyzing vapor exhaust from the extraction wells did not reflect small-scale differences in soil conditions in the upper portion of the contaminated soil unit. For example, the TVH concentration recorded from Well A (930 ppbv) was at least a factor of two greater than any discrete TVH concentration obtained from the soil gas probes. This observation is probably related to the relative contribution of gases from

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**Table 3.** Analyte Concentrations in Vapor Sampled after 16 Months of Remediation.

Probe #	Distance from Well (ft)	Probe Depth (ft)	TVH* (ppmv)	LMWHP* (ppmv)	Carbon Dioxide (%)	Oxygen (%)	Nitrogen (%)
A1	6	16	480	<5	15.3	4.6	79.7
A2	6	16	56	<5	4.3	9.4	86.3
A3	6	16	17	<5	13.8	8.3	77.8
B1	9	14	<5	<5	1.3	18.9	79.8
B2	9	14	2200	70	11.2	3.6	85.0
B3	11	14	510	10	4.8	13.5	81.7

\* Total Volatile Hydrocarbons (carbon range of C<sub>1</sub>-C<sub>6</sub>).

† Low Molecular Weight Hydrocarbons (fraction of TVH representing C<sub>1</sub>-C<sub>4</sub> gases).

various depths within the screened interval of the wells. Similarly, the 180 ppmv concentration analyzed for TVH at Well B provided a poor prediction of three discrete TVH concentrations (analyzed within eleven feet of the well), which varied from <5 to 2200 ppmv.

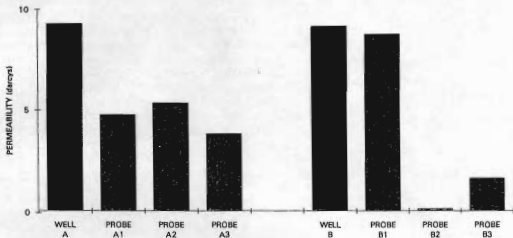
The wellhead monitoring results used to predict levels of oxygen and major fixed gases were no better than those used to predict hydrocarbon concentrations. The CO<sub>2</sub>/O<sub>2</sub> ratios obtained from the extraction wells (i.e., approximately 0.3) can be compared to a range of values from 0.07 to 3.4 for discrete soil vapor samples collected from the probes. It appears that fixed and biogenic gas data collected from the wellhead are not particularly good indicators of redox conditions, oxygen supply, or microbial activity within the capture zone. Moreover, methane and C<sub>2</sub>-C<sub>4</sub> aliphatic gases were not present in either of the well samples; however, these compounds were present in two probes within the capture zone of Well B.

These C<sub>1</sub>-C<sub>4</sub> hydrocarbon gases are indicative of methanogenic processes and the reduction of low molecular weight organic acids, which are often associated with high levels of petroleum product in soil (Marrin, 1991). Thermodynamic factors suggest that light hydrocarbon gases are readily oxidized by aerobic or denitrifying microorganisms in soils; therefore, their presence is restricted to the highly reducing zones that are often characterized by contaminated soil or groundwater. The elevated concentration of C<sub>1</sub>-C<sub>4</sub> compounds in soil vapor from probe B2 is further evidence that the exchange of soil gases (i.e., via the advective flow of air) has probably been minimal.

#### Air Permeability

In addition to comparing analyte concentrations in samples collected from the extraction wells and soil gas probes, air permeabilities measured

Figure 1. Soil Air Permeabilities.



on a large-scale and small-scale basis can be contrasted. **Figure 1** is a graphical representation of soil air permeability calculations made on the basis of flow/vacuum data collected from the two extraction wells and corresponding soil gas probes, respectively. The data suggest that air permeabilities estimated from the extraction wells were generally greater than those measured at the soil gas probes. This observation is not related to the scale of the measurement; however, it may be a reflection of differences between probe and well design. Vapor wells are screened over a substantially longer vertical interval than are the probes, and it is likely that airflow to the wells is channeled through the most permeable soils within the contaminated soil unit (which may represent only a fraction of the total screened interval).

The data presented in **Figure 1** also indicate a marked difference in the variability of permeabilities calculated among the two wells. Only slight differences in air permeability were measured between Well A and the surrounding probes (i.e., less than a factor of 2.5), suggesting that conditions were relatively homogeneous in the upper portion of the soil unit and that small-scale permeabilities were adequately represented by pilot test data. Conversely, the air permeability measured at Well B was considerably less representative of conditions in soil surrounding the well, probably due to the heterogeneity of soil conditions. Considering the nearly fifty-fold difference in air permeability measured at the wellhead and at a probe located only nine feet away, it is likely that airflow to the well is anisotropic.

The lowest air permeability measured at this site was 0.2 darcys at probe location B2, which corresponded to both the highest TVH concen-

tration (2200 ppmv) and the lowest oxygen level (3.6 percent). In fact, this TVH concentration analyzed at sixteen months into the remediation was not appreciably different from that measured at Well B during the pilot test (see Table 2). These data suggest that the soils in the vicinity of probe B2 were probably not remediated appreciably, by either SVE or biodegradation, during the cleanup period. In order to investigate whether this low permeability zone was correlated with "unremediated" soil, a sample was collected from a depth of fifteen feet near probe B2 and analyzed for TPH. The sample contained a TPH concentration of 1,500 mg/kg, which was slightly in excess of the 1,000 mg/kg cleanup limit and considerably higher than TPH levels of <5 to 350 mg/kg, which were analyzed in confirmation samples collected from other locations within the remediated soil unit.

### CONCLUSION

Conventional methods of monitoring in-situ remediation may provide "average" results for the most permeable zones affected by SVE or bioventing; however, they provide very limited information on the degree of heterogeneity within the remediation zone and on the presence of "hot spots." Although the bulk of the contamination may be successfully removed or degraded, the verification of site cleanup is based on the collection and analysis of samples from a designated number of locations. Hence, if these unremediated zones are laterally or vertically extensive, it is likely that remediation will be ineffective. If these potential hot spots can be identified early in the remediation process (or even during the pilot tests), additional wells can be installed or other treatment measures employed in order to maximize the efficiency of the selected cleanup technique.

Traditionally, more time and resources have been applied to the design, construction, and maintenance of an in-situ remediation system than to monitoring the progress of the cleanup process. With an increasing number of in-situ remediation projects failing to achieve cleanup in the anticipated time period, it is likely that a considerably greater emphasis will be placed on monitoring techniques. The use of rapid and inexpensive techniques such as the analysis of fixed and biogenic gases and the measurement of small-scale air permeabilities will likely be used to supplement the more conventional methods. ■

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