

How to Collect Reliable Soil-Gas Data for Risk-Based Applications

Part 1: Active Soil-Gas Method

by Blayne Hartman

In July 2002, I attended a conference held by the Indiana Department of Environmental Management (IDEM) in Indianapolis with special emphasis on the upward-vapor risk-assessment pathway. Issues raised repeatedly during the conference pertained to the advantages of using soil-gas data in making risk assessments and the need for having established protocols and guidance for soil-gas surveys to ensure high-enough quality data. After making a brief statement to the audience and then being swarmed by interested parties, it was clear to me that the environmental community would be well served by an article addressing this topic.

Contrary to Popular Belief...

Before diving into the meat of the topic, let me make three points to address some of the misconceptions raised at the IDEM meeting:

- Contrary to popular belief, soil-gas techniques that yield reliable data have been in existence for many years, and published regulatory protocols do exist. (I list applicable Web sites later.)
- Contrary to the prevailing opinion that soil-gas data is so variable that it can not be trusted for risk-assessment purposes, soil-gas data collected in a careful, consistent manner typically show reproducibility of +/- 25 percent. This margin of error is on the same order as indoor air measurements and is a much smaller error than that introduced by many of the assumptions in the Johnson-Ettinger (J-E) model using groundwater data.
- Contrary to popular belief, soil-gas data should be significantly less expensive (by at least a factor of two) than indoor air measurements.

Why Use Soil-Gas Data for Upward-Vapor Risk Assessment?

As was pointed out repeatedly at the Indianapolis conference, even by Dr. Paul Johnson himself, the use of actual soil-gas values, rather than values calculated from models, is preferred. The reason for this is that the measured values account for processes that are currently hard to quantify with risk models, such as volatilization from groundwater, transport across the capillary fringe, and bioattenuation. In addition, measured values will take into account the presence of vapors in the vadose zone from sources other than groundwater, such as contaminated soil or lateral vapor transport (i.e., vapor clouds).

Experience has documented that the potential error in calculated soil-gas values versus measured soil-gas values can be several orders of magnitude. If calculated soil-vapor values can differ from actual values by factors of 10 to 1,000, then the calculated vapor fluxes and in turn, the calculated room concentrations using any version of the J-E model, will be off by a similar factor. In other words, the error introduced by using calculated soil-vapor data is likely to be far greater than the errors introduced by all of the other parameters used in the model (e.g., porosity, advection, multi-layers).

Some History and Current Status of Regulatory Soil-Gas Guidance

Historically, soil-gas surveys have been used primarily for site assessment purposes to identify soil and groundwater contamination. Part of the motive for employing such surveys was that the methods were inexpensive and quick. In the absence of published U.S. EPA methods, soil-gas surveys were conducted using a variety of protocols, depending on

the operator. Indeed, in their simplest form, soil-gas surveys have been conducted by hammering a piece of galvanized water pipe into the ground and hooking up a hand-held meter. No wonder soil-gas methods got such a bad rap for data quality.

In the early 1990s, the Los Angeles Regional Water Quality Control Board (L.A. Water Board), under contract to U.S. EPA Region 9, began investigating the sources of chlorinated solvent contamination in groundwater in parts of the Los Angeles Basin. The board preferred to use soil-gas surveys as its initial investigatory method on the basis that the technique had a greater chance of detecting vadose-zone contamination.

Recognizing the lack of published protocols and noting a wide variability in techniques by firms offering the service, the L.A. Water Board, with input from many of the soil-gas firms, wrote a set of analytical guidelines for soil-gas surveys for the purpose of bringing some consistency to the data. The original document, written in 1992, has been revised several times by the L.A. Water Board (most recent version: February 1997), and adapted as recently as 2000 by the San Diego County Department of Environmental Health (DEH) for its site assessment manual (http://www.co.sandiego.ca.us/deh/lwq/sam/pdf_files/SoilGas.PDF).

As years passed, these protocols became the "standard" for most of southern California and parts of northern California. However, they focused primarily on the analysis of soil-gas samples and gave little information on the collection of these samples. Since collection methods are also extremely varied among operators and can introduce large errors, the San Diego County DEH decided that additional guidelines were needed to bridge this gap, especially

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in light of the increased emphasis on health risks resulting from vapor intrusion.

In 2001, the DEH commissioned a technical work group to write a set of collection guidelines for all soil-gas applications, including upward vapor risk. Those guidelines were completed in August 2002 and are now available in the *San Diego County Site Assessment Manual* (http://www.co.san-diego.ca.us/cnty/cntydepts/landuse/env_health/lwq/sam/pdf_files/presentations/soilvapor_guide.pdf).

These guidelines are not step-by-step protocols, but they present general topics/issues that need to be considered and fulfilled. Currently, CA-EPA, in conjunction with the L.A. Water Board and many of the local soil-gas firms, is finalizing a set of step-by-step collection protocols. These should be available on-line before the end of this year, perhaps as early as November.

Which Soil-Vapor Method to Use?

Three methods are commonly employed to measure soil-vapor/gas contamination: active, passive, and surface-flux chambers. A full discussion of the various measurement techniques is beyond the scope of this article; however, some summary thoughts will be presented here. Helpful overviews can be found in the *San Diego County Site Assessment Manual* and the *Standard Encyclopedia of Environmental Science, Health & Technology*, Chapters 11.8 and 11.9 (ISBN# 0-07-038309-X).

Active soil vapor methods consist of the withdrawal of the soil vapor from the subsurface and subsequent analysis of the vapor. These methods give concentration data (e.g., $\mu\text{g}/\text{m}^3$), which are required for calculating the contaminant flux using Fick's first law or with various versions of the Johnson-Ettinger model. Vertical profiles of the soil-vapor concentrations can be obtained to aid in determining the direction and magnitude of the flux. Active soil-vapor data can be collected and measured in real time, enabling decisions to be made in the field. The problem most often raised with

active soil-vapor data is whether the concentrations measured at any given time and day are representative of normal conditions (i.e., how "stable" are active soil-vapor data?). We'll tackle this issue in the sections ahead.

Passive soil vapor methods consist of the burial of an adsorbent in the ground with subsequent retrieval and measurement of the adsorbent. These methods give a time-integrated measurement and therefore reduce the uncertainty caused by temporal variations. However, passive soil-vapor methods only yield soil-vapor data in terms of mass (e.g., micrograms [μg] or some other form of relative units), not concentration, because the amount of vapor that comes into contact with the adsorbent is unknown. To mitigate this problem, a "conversion" of the data from mass units to concentration units is sometimes attempted, which requires knowledge of the volume of vapor that passed by the buried adsorbent during the burial time period. There is no practical way to estimate this volume; therefore passive soil-vapor data cannot be used for quantitative upward vapor-migration assessment. For this reason, this method will not be discussed further in this article.

Surface-flux chambers are enclosures that are placed directly on the surface (e.g., ground, floor) for a period of time (generally a few hours to a few days), and the resulting contaminant concentration in the enclosure is measured. By dividing the measured concentration by the incubation time, a direct value for the flux is determined. This method offers advantages over the other two methods because it yields the actual flux of the contaminant out of the ground, which eliminates some of the assumptions required when calculating the flux with a model. However, this technique is not as fast or easy to implement as the other two, it is subject to near-surface effects (i.e., are the measured fluxes "stable"?), and it gives us no idea of what may be "hiding below."

Which method to use on a given site depends upon your site-specific goals and the logistical limitations. The active soil-vapor method offers less uncertainty and more versatility than the surface-flux chamber

method for most situations. For this reason, we'll start with the active soil-gas method and tackle the surface-flux chamber method in the next issue of *LUSTLine*.

Collecting Active Soil-Gas Samples

Reported soil-vapor data depends greatly on the collection protocols. This section presents a brief description of the primary factors that can influence the measured results. Refer to the previously referenced documents for more details.

Volume of Sample Withdrawn

In my opinion, this is perhaps the most important issue influencing the integrity and composition of soil-gas samples, so I will address it first. In a nutshell, the larger the quantity of soil vapor that is withdrawn, the greater the uncertainty about the exact location from which the soil vapor came. For example, if near the surface, large extraction volumes increase the potential that atmospheric air might be drawn down the outside of the probe body. If at depth, large extraction volumes increase the potential that samples might be from a different depth or location. In addition, large purge volumes can create vacuum conditions that cause contaminant partitioning from the soil into the soil gas. All of these issues increase the potential that the collected soil-gas sample is not representative of in-situ soil vapor at the target depth. Lastly, the larger the sample volume required, the larger and more complex the sample collection system required (e.g., vacuum pumps, larger sample containers). For all of these reasons, sampling systems with small, internal dead volumes offer advantages over systems with larger, internal dead volumes, although reliable samples can be collected with the latter.

Sample Collection Through a Driven Rod versus Burial of Tubing Two techniques are most commonly used to collect samples:

- Driving a hard rod to a given depth (e.g., using hand equipment, direct-push systems) with the subsequent removal of the rod.
- Burying a small-diameter (1/8" to 1/4" outer diameter) inert tube to a given depth with subsequent

sampling after a short "equilibration" time period (20 to 30 minutes). The tubing may be buried in holes created with hand-driven rods, direct-push systems, hand augers, or drill rigs.

Both methods have been shown to give reliable, reproducible data. If the drive-rod method is used, the sample integrity is optimized if the rod is drawn through small-diameter inert tubing that runs down the center of the drive rod, as opposed to the drive rod itself.

Purge Volume The sample-collection equipment has an internal volume that is filled with air or some other inert gas prior to insertion into the ground. This internal volume, often called the dead volume, must be completely purged and filled with soil vapor to ensure that a representative soil-vapor sample is collected. Different opinions exist on the optimum amount of vapor to be purged. Some believe that, at a minimum, enough vapor should be withdrawn prior to sample collection to purge the probe and collection system of all ambient air or purge gas (one purge volume). Others believe that a minimum of three system volumes should be purged, similar to a groundwater monitoring well. Most experienced soil-vapor personnel purge a minimum of one and a maximum of five system volumes before collecting a sample. CA-EPA requires that a site-specific purge volume test be conducted at the start of a survey. In my opinion, this test is only necessary when large volumes are being collected (>500 cc). Most important is that the purge volume is consistent for all samples collected from the same site.

Excessive Vacuums Applied During Collection Soil-vapor samples that are collected under high-vacuum conditions or under a continuous vacuum may contain contaminants that have partitioned from the sorbed and dissolved phase into soil gas created by the collection process, rather than the contaminants present in the undisturbed soil vapor. For collection systems employing vacuum pumps, the vacuum applied to the probe should be kept to the minimum necessary to collect the sample and should be measured and recorded.

Probe Seals For collection systems that have large purge volumes or that are designed to collect large sample volumes, it is often necessary to seal the probe at the surface. Seals may also be necessary for small-volume systems if the soils are extremely porous and the sampling depth is close to the surface (<3 feet). Most common sealing techniques involve packing the upper contact of the probe at the surface with grout or using an inflatable seal. Seal integrity can be tested easily by allowing a tracer gas (e.g., propane or butane) to flow around the probe at the contact with the ground surface and then analyzing the collected soil-vapor samples for the tracer gas. CA-EPA requires tracer-gas tests on at least 50 percent of the probes. In my opinion, this test is only necessary at very shallow depths (<3 feet bgs), or when larger volumes are being collected (>500 cc) at <5 feet bgs, or when it is visually apparent that the surface seal is poor.

Systems with Vacuum Pumps Soil-vapor samples from collection systems that employ vacuum pumps should be collected on the intake side of the pump to prevent potential contamination from the pump. Further, because the pressure on the intake side of the pump is below atmospheric, soil-vapor samples must be collected with appropriate collection devices, such as gas-tight syringes and valves, to ensure that the samples are not diluted by outside air.

Sample Containers and Sample Storage The rule of thumb here is the shorter the time between collection and analysis, the better. While on-site analysis is advantageous to ensure sample integrity, soil-vapor samples can be collected and analyzed off-site. To minimize potential effects on the sample integrity, follow these recommended practices:

- Maximum storage time should not exceed 48 hours after collection.
- Samples should not be chilled during storage, as is common with soil and water samples.
- Gas-tight vials or canisters may be used if stored samples are to be subjected to changes in ambient pressure (e.g., shipping by air). Tedlar bags are not advised.

- For fuel-related compounds (e.g., TPHv, BTEX) and biogenic gases (e.g., CH₄, CO₂, and O₂), allowable containers include Tedlar bags, gas-tight vials (glass or stainless steel), and Summa canisters.
- For halogenated compounds (e.g., TCE, TCA, PCE), allowable containers should be gas tight and also dark to eliminate potential effects due to photodestruction. Tedlar bags are generally not considered to be reliable for low-contaminant levels for storage times exceeding a few hours. For higher-contaminant levels (>1 µg/L-vapor), storage in Tedlar bags for up to 24 hours may be okay.

Collection of Soil Vapor Samples with Summa Canisters

Because Summa canisters are typically large-volume containers (e.g., three to six liters) under high vacuum, extra care should be exercised during sample collection to ensure that air from the surface is not being inadvertently sampled or that desorption of contaminants from the soil does not take place. The possibility of breakthrough from the surface increases the closer to the surface the samples are collected (i.e., less than five feet below grade). To minimize the potential of surface breakthrough, there should be seals around the probe rod at the surface. To minimize the potential desorption of contaminants from the soil, Summa canisters should be filled at a rate that minimizes the vacuum applied to the soil and the turbulent flow at the probe tip. CA-EPA's guidance requires this rate to be less than 200 mL/min, although the technical basis for this specific value is unclear.

Transient Effects Influencing Measured Soil-Gas Values

There are four transient effects that can influence soil-gas values: temperature, barometric pressure, precipitation, and gravitational effects. So let's look at each of these.

- **Temperature** This can have an effect on soil vapor concentrations, since both the vapor pressure and water solubility of compounds are temperature dependent. However, temperature variations decrease with depth in the soil column and

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are unlikely to have large influences on concentrations at five feet below grade or greater. In areas with large seasonal temperature variations, the most conservative values will be collected in the warmer months. Measurement of temperature at collection depth is easy and can help to quantitate any expected variation. In areas with small temperature variation, the variation at typical collection depths (>3 feet bgs) is typically less than 2° C. This level of temperature variation will not create a measurable effect.

- **Barometric Pressure** Changes in barometric pressure can lead to a pressure gradient between the soil vapor and the atmosphere, creating a flow of soil vapors out of the vadose zone during barometric lows and into the vadose zone during barometric highs. The potential effects decrease with increased sampling depth and are generally less than a factor of two at depths of five feet below grade or greater. Measurement of barometric pressure is advised for samples collected at depths shallower than five feet below grade for risk-based applications.
- **Precipitation** Infiltration from rainfall can potentially impact soil vapor concentrations by displacing the soil vapor, dissolving volatile organic compounds, and by creating a "cap" above the soil vapor. In practice, infiltration from large storms only penetrates into the soil on the order of inches. Hence soil-vapor samples collected at depths greater than three feet below grade are unlikely to be significantly affected. Soil vapor samples collected closer to the surface (<3') may be affected, and it is recommended that measurements of percent moisture of the soil be taken if shallow sampling is performed during or shortly after significant rainfall (>1").
- **Gravitational Effects (Earth Tides)** Earth tides (movement of soil vapor in response to variations of the earth's geometric shape due to gravitational pull) have been

promoted as a factor on soil-vapor movement. However, in reality, fluctuations in water levels during periods of maximum gravitational pull (new and full moons) are less than 0.1 foot. Hence, earth tides do not have a significant effect on soil-vapor movement and concentration.

Analysis of Active Soil-Gas Samples

As stated previously, regulatory guidance for soil-gas samples has existed since 1992. This guidance is similar to the U.S. EPA analytical methods for water and soils in SW-846 and yields equivalent-quality data. The largest modification from SW-846 methods is the limited number of target compounds (22 in total) chosen to cover the most common aromatic and solvent compounds. The San Diego County version expands and divides the target compound list into three different groups: fuels, solvents, or mixed-use (http://www.co.san-diego.ca.us/deh/lwq/sam/pdf_files/SoilGas.PDF).

Primary analysis-related factors that can have an effect on soil-vapor data are:

- **Instrumentation** The typical instruments used for the analysis for most compounds are gas chromatographs that are equipped with a variety of detectors. VOCs are detected and quantified with photoionization detectors (PIDs), electron capture detectors (ECDs), electrolytic conductivity detectors (EICDs), and mass selective detectors (GC/MSs). In some cases, depending on the project goals, simple flame ionization detectors (FIDs) may be suitable. The GC/MS provides more selectivity and is advantageous at sites where a variety of compounds may be present and cause interferences. At gasoline sites, the GC/MS is the preferred instrument for risk assessments due to the high potential for the alkanes to interfere with benzene and the oxygenates.
- **On-Site versus Off-Site Analysis** On-site analysis offers significant advantages over off-site analysis, especially for risk assessments since the real-time data enables additional locations to be

added, either spatially or vertically. Laboratory-grade instruments, including mass spectrometers, are capable of being transported into the field, and they can fulfill the analytical protocols referenced previously.

- **Detection Limits** Most analytical instruments can readily reach detection levels of 0.1 µg/L (100 µg/m³) in the vapor (beware, 1 µg/L-vapor is not equivalent to 1 ppbv) using 10 cc to 40 cc of sample. Programs requiring lower detection limits (1 to 10 µg/m³) typically require larger sample volumes (>1000 cc) and are usually performed by collecting samples in a Summa canister, with subsequent analysis off-site by an air-concentration method (e.g., TO-14 or TO-15). Because soil-gas concentrations can be 1,000 to 100,000 times higher than indoor air concentrations, the potential for carryover from "hot" samples is much greater. To avoid this, every Summa canister used for soil-gas samples should be cleaned and verified clean by analysis when used for risk assessments. An alternative approach for very low detection limits that eliminates the use of Summas is to use on-site analysis with the GC/MS in SIM mode or, depending on the VOCs of concern, by Method 8021 (PID/EICD/ECD).

Issues Specifically Related to Risk Assessments

Sample Location and Spacing

Enough samples should be collected to allow a representative estimate of the average flux to the base of the existing or future structure. At a minimum, samples should be collected at the location of highest vadose-zone contamination near or under the structure and at each corner, or along each side, of the structure (inside if logistics allow, immediately outside if not). Real-time results can be extremely advantageous, because additional locations can be added around or inside the structure to better define the most reasonable value to use in the risk calculation. How the sample results are averaged (e.g., straight average, average plus two standard deviations) needs to be specified by the regulatory group

that has jurisdiction.

Sampling Depths For sites where near-surface sources are not suspected (e.g., fuel sites with USTs), I recommend that samples initially be collected at a depth of five feet below the structure/basement or ground surface. The logic here is two-fold: (a) this depth is generally deep enough to minimize any near-surface and transient effects on the soil-vapor values as discussed previously and (b) measured soil-vapor values at this depth will be more representative of values near the enclosure than deeper samples.

At sites where there is reason to suspect shallower contamination (e.g., dry cleaners, sites with solvent usage at the surface), or where conditions don't allow deeper samples (e.g., high water table or gravelly soils), or where the data from five feet fail the risk calculation, the collection of shallower samples (<5 feet) may be appropriate. If soil-vapor data from depths less than five feet below grade are collected, additional sampling events may be appropriate to ensure representative values, especially if the measured values yield risks that are near acceptable levels. In such cases, the burial of mini-vapor monitoring probes (implants) is an easy and inexpensive way to get repetitive data (see below).

I want to point out that the latest version of the U.S. EPA vapor-intrusion guidance implies a preference for deeper samples (i.e., 15 feet). My recommendation is not in agreement with this preference. If deeper samples are desired, all the collection methods/issues described in this article apply. In addition, it is important that you remember that the potential for vacuum stripping of contaminants out of the pore water/groundwater will increase as the percent water content goes up (i.e., in the capillary fringe and near the water table).

Sample Frequency/Reproducibility of Data Typically, a single sampling event should be sufficient to assess this risk pathway, especially if collected at deeper depths (>5 feet bgs). In some situations, additional sampling events may be appropriate; for example, where the calculated risk from the first sampling event is close to acceptable levels, or for shall-

low sampling depths, or if sampling takes place during the winter in areas with large seasonal temperature variations. In such situations, the burial of mini-vapor monitoring probes (implants) is an easy and inexpensive way to get repetitive data (see below). One simple and inexpensive approach is to measure the soil-gas values in the morning and again at the end of the day. If the results match up well, then you can conclude the sampling. If not, return the next day and repeat the procedure until the variability can be assessed.

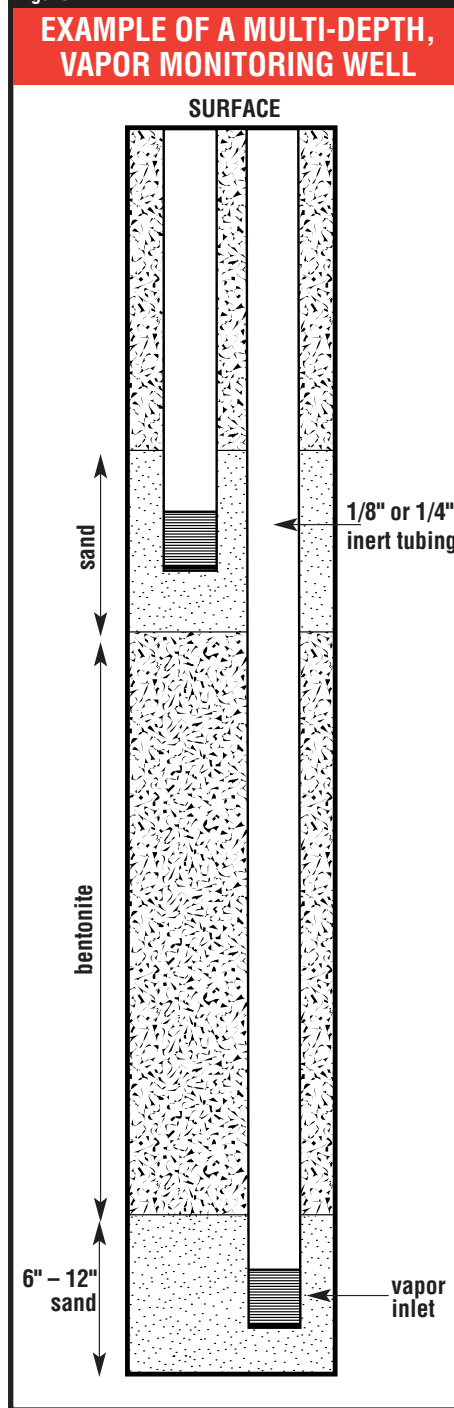
Mini-Vapor Monitoring Probes/Implants Mini-vapor monitoring probes (implants) consist of small diameter (e.g., 1/8" or 1/4" outer diameter) inert tubing with a perforated tip at the bottom (refer to Figure 1). The tubing allows for a seamless installation to depths of hundreds of feet and low internal dead volumes for easy sampling. Mini-vapor probes can be emplaced using hand augers, hand soil-vapor equipment, or direct-push systems, or can be lowered down the open drill pipe of hollow-stem and percussion drilling rigs. Several choices of perforated tips are available, including stainless-steel screens, slotted PVC pipe, and aluminum or ceramic tips.

The tube and tip are emplaced to the target depth, buried with 6 to 12 inches of sand, and then sealed to the surface with bentonite. The small tubing enables multiple tubes to be buried in the same borehole when vertical vapor gradients are desired ("nested vapor wells"). The surface end of the vapor tube is capped with a gas-tight Swagelok nut and cap or with a gas-tight valve as desired. The mini-vapor probe can be terminated at the surface with a variety of completions, such as locking well covers.

Recommended Sampling Protocol for Determining Upward Vapor Migration Risk

I recommend the following procedure for collecting near-surface soil-gas data with the intent of determining the upward-vapor flux into an existing or future room/building. This protocol is based upon the approach we have been using in Southern California for some time:

Figure 1



1. Collect active soil-vapor data at five feet below grade at enough sampling points under or near the building to give a reasonable estimate of the subsurface soil-gas concentration under the building footprint. At a minimum, samples should be collected at the corners or sides of the existing or future building and the location of highest contaminant concentration under the building (if determined previously). If the location of the future building is unknown,

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collect soil-vapor data at five feet below grade spatially across the site to identify the location of highest concentration. If a surface source of contaminants is suspected, collect at least one or two samples closer to the base of the building (one to two feet below) to validate that the five-foot samples are representative of the subbuilding soil-gas concentration.

2. Determine the health risk from the soil-vapor value using the method allowed by the local oversight agency (e.g., J-E model, default attenuation factor). If the risk calculation indicates that upward vapors pose no threat to human health, then submit a formal request for closure to the governing agency.
3. If the risk calculation indicates that upward vapors may pose a threat to human health, then either add more sampling locations spatially under the building or repeat steps 1 and 2 at a shallower depth. The logic behind this recommendation is that additional spatial samples under the footprint will yield a more representative subbuilding value, and shallower samples might show lower concentrations due to bioattenuation- and trans-

port-related factors (especially in the case of nonchlorinated compounds). Alternatively, consider an approach such as collection of indoor-air data or direct measurement of flux with surface-flux chambers.

4. If soil-vapor data are to be collected at depths less than five feet below grade, or if the risk calculation from the initial set of data is borderline, repeated measurements may be appropriate to ensure that the measured soil-gas values are representative.
5. Vertical profiles of the soil gas may be useful to document bioattenuation and to reduce near-surface variability. In such situations, it is recommended that data be collected at a minimum of three locations vertically from one foot to five feet to ensure that vertical variations are characterized adequately. Measurements of oxygen and carbon dioxide should be included if bioattenuation is being assessed.

For subsurface enclosures, such as basements or utility trenches, the same protocol can be used; however, soil gas samples should be collected from three to five feet below the floor (rather than bgs). Additionally, it may be necessary to also consider the potential flux through the walls in

addition to the floor. Assuming a contaminant source deeper than the enclosure, the most conservative assumption is to assume the flux through the walls is equal to the flux through the floor. In this case, the total flux into the room would be equal to the flux through the floor times the combined surface area of the floor and the walls.

For near-surface sources, this assumption is not safe as horizontal permeability is often much greater than vertical permeability. In such situations, a soil-vapor measurement should be made on each side of the wall (i.e., three to five feet away) and the flux through the wall should be computed separately. The total flux into the room would then be computed by summing the individual fluxes through the floor and walls. ■

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