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December 20, 2005

Mr. Jerry Wickham
Alameda County Health Care Services Agency
1131 Harbor Bay Parkway, Suite 250
Alameda, California 94502-6577

Alameda County
DEC 21 2005
Environmental Health

Re: **Plume Delineation Work Plan**
Former Shell Service Station
2703 Martin Luther King Jr. Way
Oakland, California
SAP Code 129449
Incident No. 97093397



Dear Mr. Wickham:

Cambria Environmental Technology, Inc. (Cambria) prepared this *Plume Delineation Work Plan* on behalf of Equilon Enterprises LLC dba Shell Oil Products US (Shell). This work plan is being submitted, as proposed in Cambria's November 15, 2005 *Site Investigation Report*, and as requested in Alameda County Environmental Health (ACEH) correspondence dated November 21, 2005 to provide offsite delineation of constituents in soil, groundwater, and soil-gas.

SITE LOCATION AND DESCRIPTION

The site is a former service station located on the northwest corner of Martin Luther King Jr. Way and 27th Street in a commercial and residential area of Oakland, California (Figure 1). The site layout consisted of a service station building, two dispenser islands, three underground fuel storage tanks (USTs), associated product piping, and a waste oil UST (Figure 2). Until recently, the station building was used as a repair shop and with two service bays. Currently, the site is used for storage and some auto repair work by the property owner.

SITE BACKGROUND

Site Use: A Shell service station operated on the property from approximately 1959 to 1979. Three fuel underground storage tanks (USTs) associated with the former Shell service station were removed after Shell terminated operations at the site.

In 1979, Acme West Ambulance Company (Acme) purchased the site and installed a 2,000-gallon UST for gasoline storage. Acme sold the property to Auto-Tech West (ATW) in 1986. According to an August 25, 1986 ACHCSA inspector's report, ATW reportedly never

used the UST, although a 150-gallon aboveground waste oil tank, a 15-gallon carburetor cleaner tank, and a parts cleaning tank with solvent were reportedly in use.

Currently, the site is occupied by ATW and, until recently, was utilized as an automotive repair shop. The current site operator uses the northwest corner of the property and the wooden car port for storage of such things as non-operational automobiles, portable gasoline containers, tires, and drums which are possibly used for waste oil collection and storage.

A complete description of historical investigative activities was presented in previous documents, and most recently in Cambria's November 21, 2005 *Feasibility Study Work Plan*, and will be included in the subsequent technical report for this work. For brevity, that information is not repeated in this document.



TECHNICAL RATIONALE

In addition to the two wells desired to perform an adequate DPE test for the feasibility study (MW-6 and MW-7), further delineation of the groundwater and soil-gas plumes was recommended in Cambria's November 15, 2005 *Site Investigation Report*. In correspondence dated November 21, 2005, the ACEH identified that previously requested activities were not performed during the August 2005 field event, and that they be included in this work plan. Thus, the proposed scope of this work plan and the technical rationale are provided below. Proposed sample locations are depicted on Figure 2.

- To provide delineation of the groundwater plume in the vicinity of GP-7, one additional onsite monitoring well (MW-8) is proposed;
- To delineate the lateral extent of groundwater impact to the north, northwest, west, southwest, and south of the site, seven offsite wells (MW-9 through MW-15) are proposed;
- To provide delineation and monitoring of the soil-gas plume, six onsite soil vapor probes (VP-1 through VP-6) and eight offsite soil vapor probes (VP-7 through VP-14) are proposed;
- To provide a grab groundwater sample from a boring for comparison with results from monitoring well MW-5 (as requested previously by ACEH), boring B-23 is proposed;
- To assess the concentrations of total lead in soils beneath this site (as requested by ACEH), one soil sample from MW-6, MW-7, MW-8, and B-23 will be analyzed for total lead.

SCOPE OF WORK

Access Agreements: Prior to doing work on privately owned property, Shell must obtain written authorization to access the property for the proposed work. Access agreements have been forwarded to each property owner where an offsite boring or well is proposed. No work will be performed at private property without an executed access agreement.

Permits: We will obtain necessary well and boring installation permits from the Alameda County Public Works Agency (ACPWA). Further, for work proposed within the public right of way, an Encroachment Permit will be obtained from the City of Oakland.

Site Health and Safety Plan: We will prepare a comprehensive site safety plan to protect site workers. The plan will be reviewed and signed by each site worker and kept on site during field activities. Where necessary, a traffic control plan will also be prepared to address traffic safety.

Utility Clearance: Cambria will mark proposed drilling locations and will clear the locations through Underground Service Alert prior to drilling. Also, a private utility line locating service will be scheduled to further ensure that no subsurface utilities are located at the proposed boring positions. To further minimize potential impact to any unidentified subsurface utilities, the top five feet of each boring will be cleared to at least 3 inches larger than the lead auger by hand auger.

Site Investigation: Twenty three (23) soil borings (MW-8 through MW-15, B-23, and VP-1 through VP-14) are proposed at the approximate locations shown on Figure 2. Depending on access, the monitoring wells (MW-8 through MW-15) and boring B-23 will be advanced using hollow-stem auger equipment, and will extend to approximately 20 fbg, and the soil vapor probes (VP-1 through VP-14) will be installed using hand-auger equipment to approximately 5.5 fbg.

Under the direct supervision of a California professional geologist, a Cambria staff geologist will supervise the drilling and describe encountered soils using the Unified Soil Classification System and Munsell Soil Color Charts. After borehole clearance, continuous soil sampling will be attempted. Soil samples will be retained for possible chemical analyses at five-foot intervals, at the soil-water interface, at major changes in lithology, or intervals with obvious petroleum impact. Using a calibrated photo-ionization detector (PID), organic vapors will be measured at least every five feet in the well borings and every foot in the vapor probe borings. Cambria will prepare an exploratory boring log for each boring and PID measurements will be recorded on the logs.



Soil samples designated for chemical analyses will be retained in stainless steel or brass sample tubes. The tubes will be covered on both ends with Teflon sheets and plastic end caps. Soil samples will be labeled, entered onto a chain-of-custody record, and placed into a cooler with ice for transport to a State of California certified laboratory for analyses. Following collection of soil samples, a grab groundwater sample will be collected from boring B-23 using a disposable bailer. Water will be transferred to laboratory supplied containers appropriate for the proposed analyses. Following completion of soil and groundwater sample collection, the monitoring wells will be constructed as described below, and boring B-23 will be closed by filling with a cement-bentonite grout mixture to within 4 inches below grade and capped either with asphalt patch or concrete tinted to match the surrounding surface.

Monitoring Well Installation: Well construction specifications will be determined in the field based on the nature of subsurface material encountered. A diagram of typical monitoring well construction is included as Figure 3. It is anticipated that perforated intervals of the proposed wells will extend from 5 to 20 fbg using 0.020-inch circumslot screen. A sand filter-pack will be placed from the bottom of the well up to two feet above the top of the well screen followed by a two-foot thick bentonite seal and cement grout to grade. Each well located in an area of vehicular traffic will be secured with a locking cap under a traffic-rated well box. At locations where traffic is not a concern, the wells may be finished above grade, protected by a locking stovepipe monument.

Well Development and Sampling: Blaine Tech Services, Inc. (Blaine) of San Jose, California will develop the new groundwater monitoring wells prior to sampling. After well development, Blaine will sample the site groundwater monitoring wells according to the existing sampling schedule and submit the samples to a State of California certified laboratory for chemical analyses.

Wellhead Survey Activities: Following monitoring well installation, a licensed surveyor will survey wellhead elevations relative to mean sea level and the latitude and longitude of each well location.

Soil and Groundwater Chemical Analyses: One grab groundwater sample from B-23, and selected soil samples from the soil borings will be analyzed for TPHg and BTEX by EPA Method 8021. Additionally, one soil sample from borings MW-6, MW-7, MW-8, and B-23 will be analyzed for total lead. A standard two-week turn-around time will be requested for laboratory results.

Soil Vapor Probe Installation: The vapor probes will be installed using hand auger equipment. One interval will be screened at each location at approximately 4.75 to 5.0 fbg. A diagram of typical vapor probe construction is included as Figure 4. If encountered, zones of higher permeability will be targeted for screening. The soil will be screened with a photo-ionization detector (PID) and the PID readings will be noted on the boring logs.

Each probe will consist of 0.25-inch inside diameter Teflon tubing, with no greater than 3-inch lengths of perforated screen. The bottom of the tubing and the screened interval will be wrapped with stainless steel screening to avoid potential clogging with soil. Teflon tape will be used to secure the screen on the tubing. One-inch diameter tremie pipe will be used to install the vapor probe to ensure appropriate placement of the screen interval. A clean, fine-grained silica sand filter pack will be installed from 6-inches below to 6-inches above the screened interval (4.25 to 5.5 fbg). Three inches of bentonite pellets will be placed on top of the filter pack sand (4.0 to 4.25 fbg) and the remaining boring will be filled with bentonite slurry. Each vapor probe will be sealed from the surface using a traffic-rated well box, in the same manner described for monitoring wells.

Soil-Vapor Sampling: Because a 5-day DPE pilot test is scheduled to occur within two weeks of the installation of these probes, the soil vapor probes will be sampled within two weeks following their installation. Sample collection procedures are detailed in Appendix A – *Guidance on Use of Soil-Gas Surveys to Assess Vapor Transport to Indoor Air*, prepared by Equilon Enterprises LLC dba Shell Oil Products US.


For sampling, a flow meter/controller will regulate the flow of air extracted from the tubing by a purge pump. Approximately three tubing volumes will be purged from each vapor point over a period of approximately 10 minutes prior to sample collection. A tubing purge volume calculator is presented as Graph 1. Immediately after purging, soil-vapor samples will be collected over an approximate 30-minute period using 1-liter Summa canisters.

Soil-Vapor Chemical Analyses: The vapor samples will be kept at ambient temperature and submitted under chain-of-custody to a state certified analytical laboratory for analysis. The samples will be analyzed for BTEX by EPA Method TO-14A Modified and for TPHg by EPA Method TO-3 Modified.

Utility Vault Box Screening: During the field activities, utility vault boxes at the site and in public right-of-way within 50 feet of the site will be accessed for screening with a PID. Prior to any use of the PID, it will be calibrated in accordance with the manufacturer's suggested

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protocol. Each vault box lid will be opened as little as possible to enable insertion of the PID tip. The PID will be allowed to screen the air within the vault box for approximately 60 seconds, with the PID readings recorded every 15 seconds. The location of each vault box will be noted on a site map and a description of each will be recorded in the field notes, along with the PID measurements.



Report Preparation: Following the receipt of analytical results from the laboratory, Cambria will prepare a written report that will include field procedures, figures depicting all sample locations, tabulated laboratory results, complete certified analytical reports, boring logs, and conclusions. Because the field work will be done in several mobilizations due to negotiating access and encroachment, the initial technical report will include documentation of the January well and boring installations (MW-6 through MW-8, B-23, and VP-1 through VP-6). Report addendums will need to be submitted for subsequent activities. Groundwater data from the monitoring wells will be incorporated into the existing quarterly groundwater monitoring reporting schedule. Results of the door-to-door survey currently being conducted is scheduled for submittal by January 10, 2006. As of December 15, 2005, we have received 9 responses out of 112 questionnaires.

Certification: The scope of work described in this work plan will be performed under the supervision of a California professional geologist or engineer.

SCHEDULE

Permitting for the onsite work is in progress. The onsite boring, wells, and vapor probes are scheduled for installation the week of January 3, 2006. Access agreements have been forwarded to offsite private property owners, and permits to install the wells or borings proposed at offsite locations will occur following receipt of an executed access agreement. Encroachment permits for wells within the public right-of-way will be initiated following receipt of agency approval of this work plan. Installation of wells MW-9, MW-10, and MW-11 will be scheduled upon receipt of the encroachment permit.

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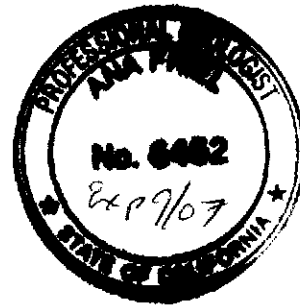
CLOSING

If you have any questions regarding the contents of this document, please call Ana Friel at (707) 268-3812.

Sincerely,
Cambria Environmental Technology, Inc.



Ana Friel, P.G.
Senior Project Geologist



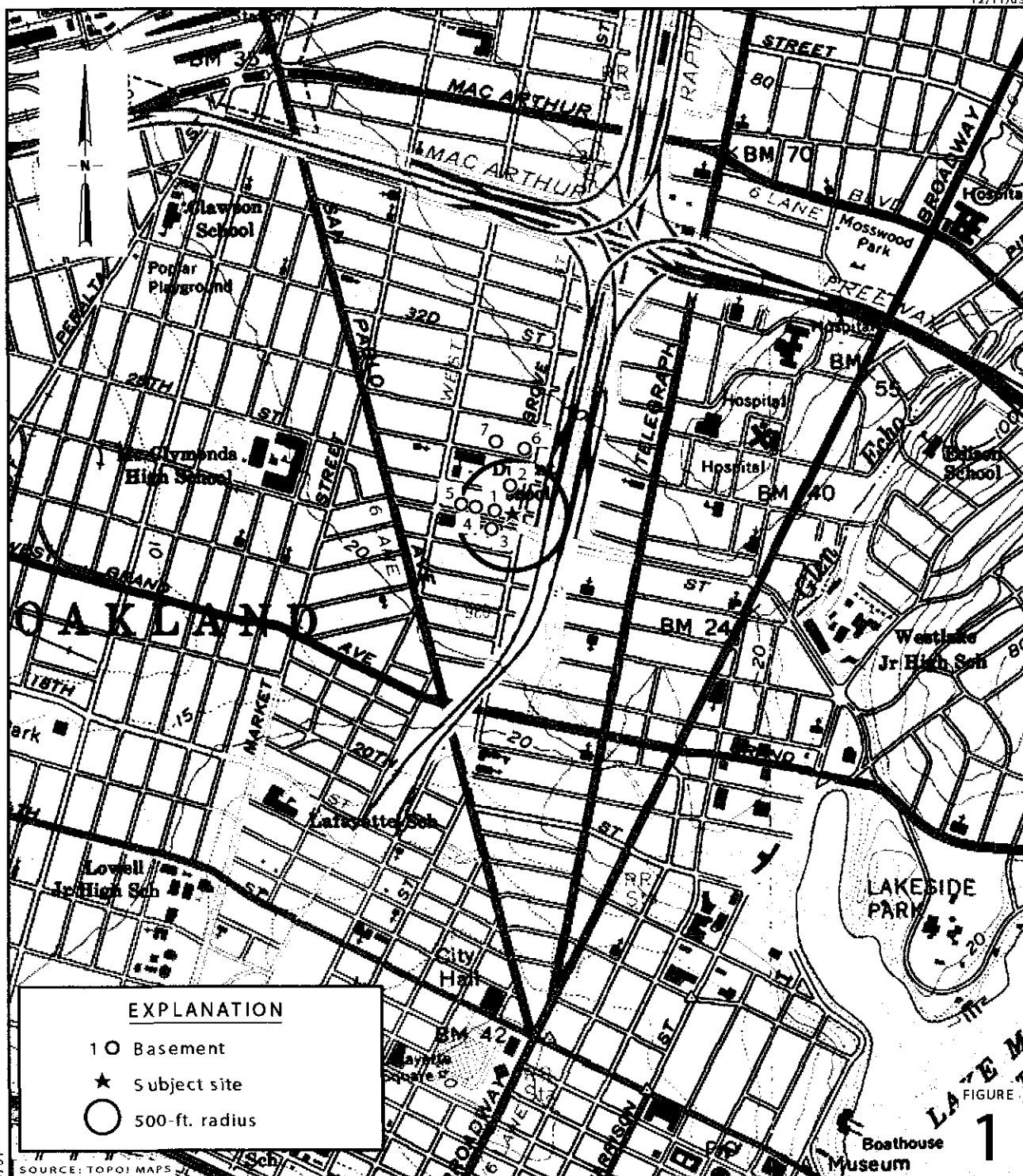
Attachments:

- Figure 1. Site Vicinity/Receptor Survey Map
- Figure 2. Proposed Sample Location Map
- Figure 3. Typical Monitoring Well Construction Diagram
- Figure 4. Proposed Construction Diagram – Vapor Probes

- Graph 1. Tubing Purge Volume Calculator

- Appendix A. Guidance on Use of Soil-Gas Surveys to Assess Vapor Transport to Indoor Air

cc: Denis Brown, Shell
Rodney & Janet Kwan, property owners



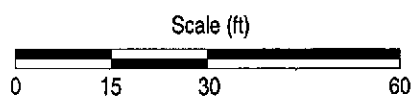
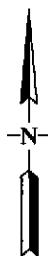
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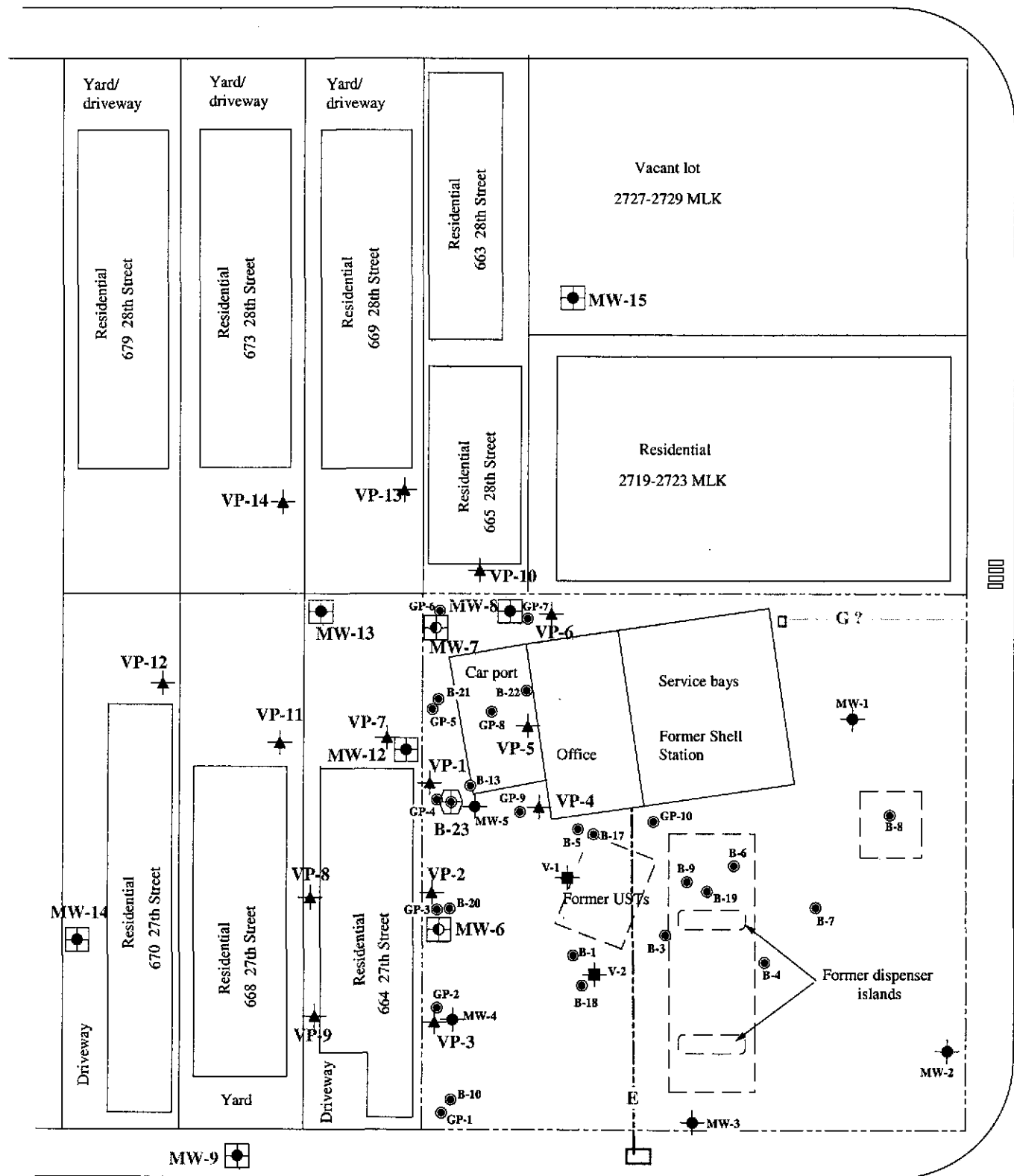
Former Shell Service Station
 2703 Martin Luther King Jr. Way
 Oakland, California



**Site Vicinity/Receptor
 Survey Map**



EXPLANATION	
●	Soil boring
⊙	Monitoring well
⊕	Soil vapor well
⊗	Proposed dual-phase extraction well
⊠	Proposed Groundwater Monitoring well
⊙	Proposed Soil-Gas Probe
⊗	Proposed Soil Boring



27th STREET

MARTIN LUTHER KING JR. WAY

⊠ MW-11

⊠ MW-10

FIGURE

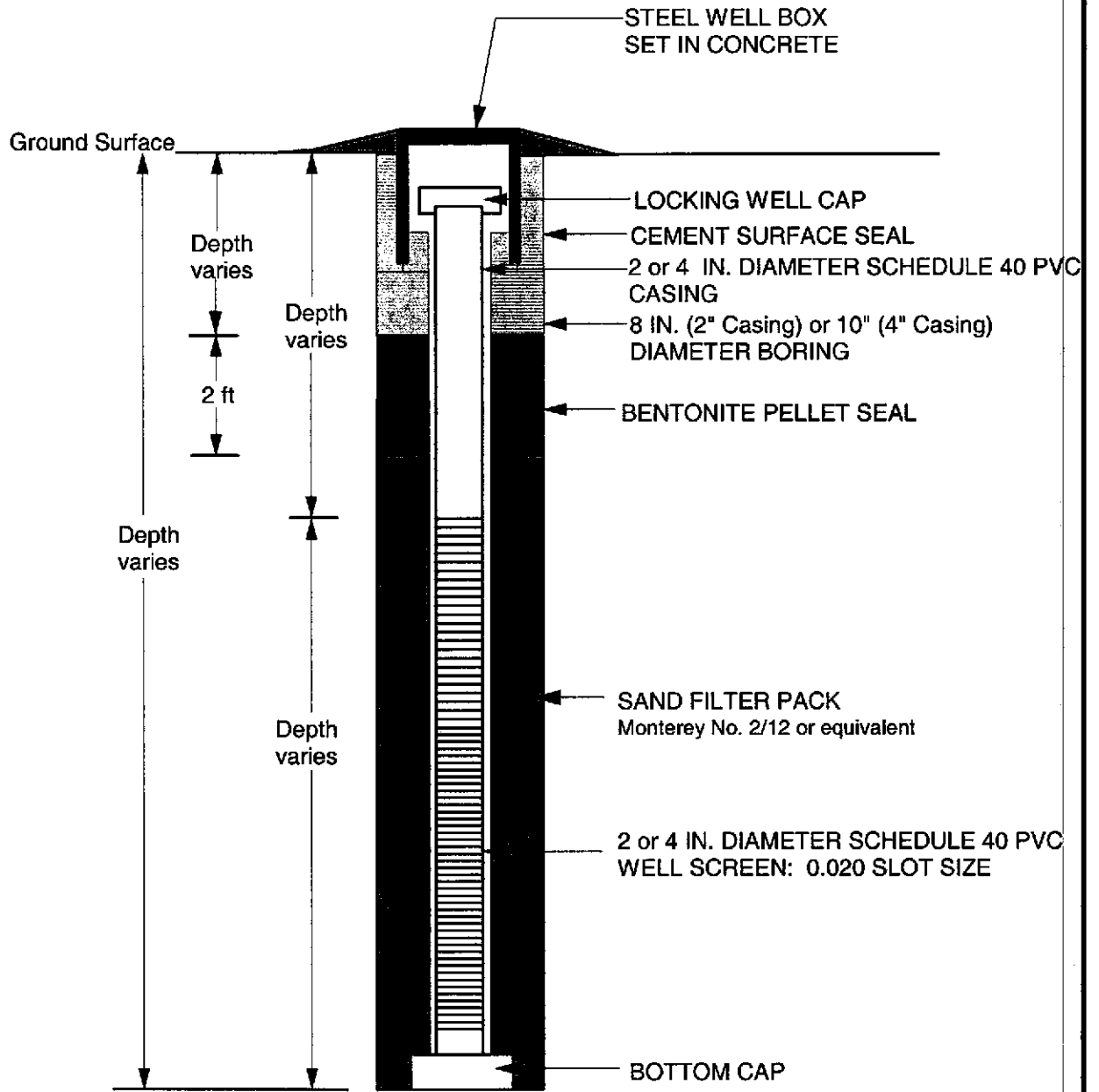
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Proposed Sample Location Map



FIGURE

3

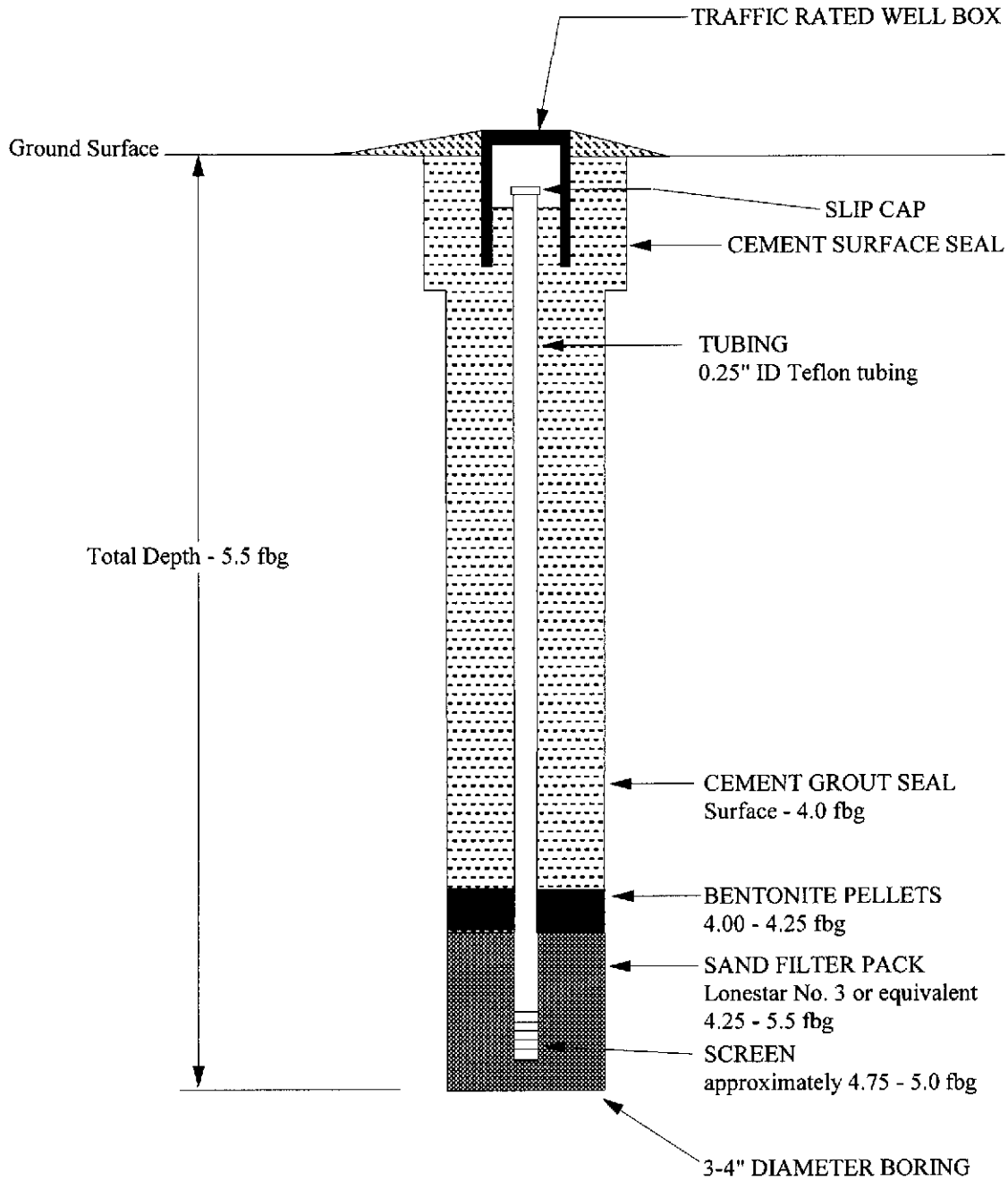
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**Typical Monitoring Well
 Construction Diagram**



FIGURE

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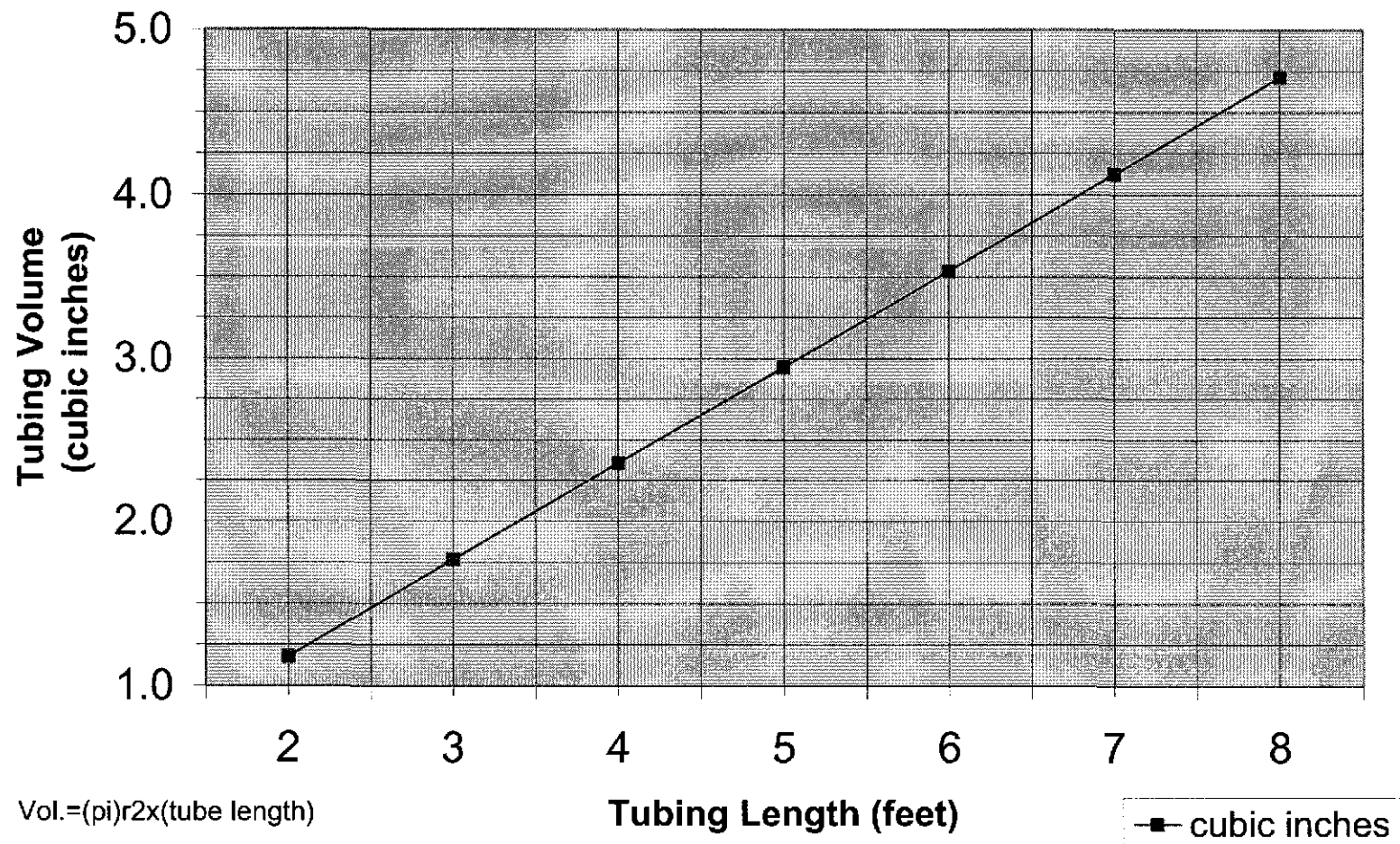
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 Oakland, California



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**Proposed Construction Diagram-
 Vapor Probes**

Graph 1 - Tubing Purge Volume Calculator
(for 0.25-inch I.D. tubing)



APPENDIX A

**Guidance on Use of Soil-Gas Surveys to
Assess Vapor Transport to Indoor Air**

GUIDANCE ON USE OF SOIL-GAS SURVEYS TO ASSESS VAPOR TRANSPORT TO INDOOR AIR



EQUILON
ENTERPRISES LLC
Shell & Tecsco Working Together

INTRODUCTION

Risk-Based Corrective Action (RBCA) has become commonplace in evaluating remediation at leaking underground storage tank (LUST) sites. At many LUST sites, migration of volatile organic compounds (VOCs) from ground water or soil into buildings or other enclosed spaces is a potential exposure pathway (see Figure 1). Soil-gas surveys can provide fundamental data needed to evaluate this pathway and should be included as part of any risk assessment. For example, soil-gas surveys can be used for:

- Tier 1 (screening-level) applications
 - to help identify chemicals of concern and maximum concentrations,
 - to delineate sources and exposure pathways,

- to detect immediate risks for combustion and human health, and
- to verify biodegradation hypotheses.

- Tier 2 and Tier 3 (site-specific) evaluations
 - to verify and predict indoor-air concentrations,
 - to quantify rates of vapor intrusion and
 - to establish site-specific target levels (SSTLs) for clean up.

The purpose of this report is to provide technical guidance on conducting soil-gas surveys at sites where long-term or chronic vapor intrusion is a concern. The reader is referred to the American Society of Testing and Materials *Standard Guide for Soil Gas Monitoring in the Vadose Zone (ASTM D 5314)* and the Environmental Protection Agency *Expedited Site Assessment Tools for Underground Storage Tank Sites: A Guide for Regulators – Chapter IV (EPA 510-B-97-)*.

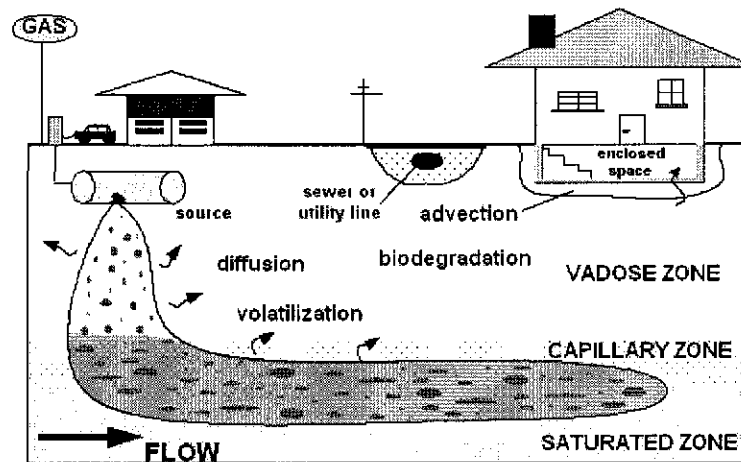


Figure 1. Conceptualization of vapor transport to indoor air at a petroleum-release site.

Table 1. Common ranges of soil-gas concentrations for compounds of environmental interest at 25°C

Compound	Saturated Vapor Concentration (g/L) ¹	Maximum Concentration in Soil Gas (g/L) ²	Minimum (Screening-Level) Concentration in Soil Gas (Residential) (g/L) ³	Minimum (Screening-Level) Concentration in Soil Gas (Industrial) (g/L) ³
benzene	4.0E-01	5.2E-03	9.9E-07	9.9E-05
toluene	1.4E-02	2.8E-03	1.4E-03	1.4E-01
ethylbenzene	5.5E-02	1.2E-03	3.5E-03	3.5E-01
o-xylene	3.8E-02	3.8E-04	1.6E-02	1.6E+00
trichloroethylene	4.6E-01	4.6E-01	4.8E-06	4.8E-04
1,1 dichloroethylene	2.4E+00	2.4E+00	1.6E-07	1.6E-05
1,1,1 trichloroethane	9.4E-01	9.4E-01	3.5E-03	3.5E-01
tetrachloroethylene	1.5E-01	1.5E-01	1.4E-05	1.4E-03

¹Calculated from ideal gas law.

²Calculated by assuming the following mole fraction composition for gasoline: benzene – 1.3%, toluene – 20%, ethylbenzene – 3%, and o-xylene – 1%.

³Calculated using the Johnson and Ettinger (1991) model assuming chemical, building, and soil parameters defined by the U.S. Environmental Protection Agency (1997).

001) for more detailed discussions of soil-gas surveys and various methodologies. This report does not evaluate cases where high concentrations of vapors are present in enclosed spaces (e.g., utility, sewer, and dry-well conduits) that pose flammability and/or acute health risks. These cases typically require immediate attention and response.

THEORETICAL PRINCIPLES

Transport of VOCs to indoor air is a complex phenomenon involving partitioning, migration, and biodegradation (see Figure 1).

- **Partitioning:** The potential for vapor migration to indoor air is greatest for compounds that strongly partition to the gaseous phase. Partitioning of a compound to the gaseous-phase is defined by Raoult's Law (gaseous/immiscible phase partitioning) and Henry's Law (gaseous/aqueous phase partitioning), which, in turn, is defined by the vapor pressure and solubility of a compound, which are temperature and pressure dependent. At LUST sites, benzene, trichloroethylene, 1,1 dichloroethylene, 1,1,1 trichloroethane, and tetrachloroethylene are potential chemicals of concern due to their high source concentrations, vapor pressures, Henry's Laws, and human toxicities (see Table 1).
- **Migration:** Migration of VOCs to indoor air is governed by gaseous-phase advection and gaseous-phase diffusion. Gaseous-phase advection, caused by pressure gradients near foundation walls, is the more dominant migration mechanism near the receptor. Gaseous-phase diffusion, caused by concentration gradients between the source and the receptor, is the more dominant migration

mechanism away from the receptor. The magnitude of these mechanisms is dependent upon soil type, source concentration, and building characteristics. Seasonal effects, including the presence of a frost layer and variations in soil moisture content, water table elevation, barometric pressure, and biodegradation rate, can also affect rate of vapor intrusion. Vapors will tend to migrate toward areas of lower pressure and concentration and along paths of least resistance (e.g., backfill materials surrounding sewer and utility lines, tree roots, or drains and cracks in basement foundations).

- **Biodegradation:** Depending on substrate (VOC), electron acceptor (e.g., oxygen -- O₂), and nutrient conditions, biodegradation can also play a significant role in limiting transport to indoor air, especially for benzene and other biodegradable petroleum compounds. This mechanism, however, is not considered in most risk assessments.

APPROACH

The following approach is intended to serve as guidance for conducting soil-gas surveys at LUST sites where vapor transport to indoor air is a potential exposure pathway. The actual approach that is taken will depend on site-specific conditions, project confidence, and available resources.

The approach for conducting a soil-gas survey is divided into four phases:

- Phase I: Method Selection and Sampling Design,
- Phase II: Borehole Development and Soil Sampling,

- Phase III: Probe Construction and Installation
- Phase IV: Sample Collection, and
- Phase V: Analysis.

Phase I: Method Selection and Sampling Design

The two principal methods applied in soil-gas surveying are active and passive. Selection of an appropriate method depends on the site-assessment objectives.

- **Active Sampling:** Active sampling is a technique that involves collecting a whole air (grab) sample by induction of air flow either directly into an analytical instrument (detector) or into a gas-tight container for subsequent analysis. Active sampling is performed at fixed or temporary locations and generally is generally more costly than passive sampling. The active method provides quantitative real-time data and is recommended for risk assessment.
- **Passive Sampling:** Passive sampling is used primarily for qualitative (field screening) purposes. Soil-gas samples are collected in sorbent cartridges or flux chambers without induction of air flow. The sample is retrieved at a later date for analysis. Passive sampling is not recommended for risk assessment because soil-gas concentrations can not be directly measured.

The design of a soil-gas sampling system requires fundamental knowledge of source location, soil stratigraphy, and potential exposure pathways. These data can be determined through reconnaissance sampling using a Geoprobe® and on-site soil-gas analyses (see Table 2) or during soil sampling (see Phase II: Borehole Development and Soil Sampling). To characterize the soil-gas pathway, soil-gas probes are generally placed between the source (soil or ground-water plume) and the receptor (building foundation). It is often advantageous to maximize the number of soil-gas probes placed in this region because of the minimal cost and effort required for additional probe installation.

- **Vertical Sampling:** Soil-gas probes should be placed in nests (clusters) approximately 2 to 3 ft apart in shallow vadose zone systems (< 10 ft) and 3 - 5 ft apart in deeper systems according to the configuration shown in Figure 2. Particular attention (closer spacing) should be given to regions near the source and near the receptor. If soil layers with significantly different

permeabilities are present, probes should be placed within the higher permeability soil units without regard to depth. These units will act as preferential pathways for vapor migration. This practice requires greater effort and expense than fixed-interval installation because the presence, thickness, and depth of target soil horizons, needs to be known *a priori*. It is therefore important to examine boring logs and conduct soil sampling to identify soil strata, perched water and clay lenses, buried structures, and recently disturbed soils or backfills. At sites where the source is present in ground water, placement of 1 - 2 soil-gas probes below the water table is often beneficial. These probes can provide more accurate water-table concentration data than conventional monitoring wells, which are typically screened over greater lengths (2 - 20 ft). In addition, these probes can provide additional soil-gas data during periods of low water-table elevation.

- **Areal Sampling:** The areal distribution of soil-gas probe nests depends on the purpose of the soil-gas investigation. For general mapping purposes, probe nests should be positioned approximately 15 - 30 ft apart in a grid pattern. Probe nests should be spaced at closer intervals (3 - 6 ft) if targeting an exposure pathway, such as near a building foundation, storage tank, or transfer conduit (sewer lines, trenches, utility vaults, pipelines and other preferential pathways). Two or more probe nests are recommended for most site assessments, even if the vapor pathway is considered well defined.
- **Repeated Sampling:** Short-term effects, such as changes in barometric pressure, water table elevation, moisture content and long-term effects, such as biodegradation and changes in source strength, can result in the appearance or disappearance of certain compounds from soil-gas over time. Depending on compound and soil type, distance from the source, and relative age of the release, response times can range from hours to days for short-term effects and from months to years for long-term effects. Repeated sampling provides a means to assess these temporal variabilities.
- **Sampling Following Precipitation Events and Probe Installation:** Because the effect of recharge on soil-gas concentrations is still uncertain, soil-gas sampling is not recommended within 2 - 3 days of a precipitation event. In addition, soil-gas sampling should be conducted no earlier than 3 - 4 weeks following probe

Table 2. Comparison of commonly employed analytical methods

Instrument	Compounds Detected	Detection Limits	Data Quality Level	Advantages	Limitations
Detector tubes	Aliphatics and aromatics, alcohols, inorganics	0.1 – 8,000 ppm	1A/1B	Inexpensive Easy to use Provides immediate results Compound specific	Low sensitivity (mainly for screening purposes) Cross-contamination by other compounds Affected by humidity, sample flow rate, temperature extremes, storage conditions and shelf life
Portable Photoionization Detector (PID)	Aromatics (e.g., BTEX), some aliphatics, less methane	1 - < 300 ppm	1A/1B	Inexpensive Easy to use Provides immediate results	No inorganic analyses Low sensitivity (mainly for screening purposes) Inconsistent readings Can not detect methane (CH ₄) and thus may produce false low readings when CH ₄ concentrations exceed 1 % Instrument response can be affected by high relative humidity (> 90%), dust, temperature (< 0°C), and electrical currents (power lines)
Portable Flame Ionization Detector (FID)	Aliphatics (e.g., butane), less sensitive to aromatics (e.g., BTEX)	1 - > 1,000 ppm	1A/1B	Inexpensive Easy to use Provides immediate results	Low sensitivity (mainly for screening purposes) Inconsistent readings High CO ₂ , low O ₂ (<15 %) Requires a hydrogen source and more training than PID High flow rates (~ 2L/min) needed for analysis Instrument response can be affected by wind and temperature (< 0°C) High CH ₄ concentrations may be interpreted as contamination
Portable Explosivity Detector (ED)	Combustible gas mixture (gasoline, O ₂ , and CH ₄)	> 100 ppm	1A/1B	Inexpensive Easy to use Provides immediate results Less sensitive to environmental effects than PIDs or FIDs	Low sensitivity (mainly for screening purposes)
Portable Gas Chromatograph (GC)	Aromatics and aliphatics, inorganics, and chlorinated compounds	1 ppb – >1,000 ppm	2	More quantitative than typical PIDs and FIDs More easily transported than transportable GCs (no carrier gas – hydrogen, helium) needed Relatively short analysis time (< 10 minutes)	Requires power supply Relatively long analysis time (10 – 60 minutes) Expensive Higher operator training than other portable detectors
Transportable Gas Chromatograph (GC)	Aromatics and aliphatics, inorganics, and chlorinated compounds	1 ppb – >1,000 ppm	2/3	Provides better quantification and identification of compounds than portable GCs High sensitivity Consistent measurements	Requires power supply Relatively long analysis time (10 – 60 minutes) Expensive Higher concentration samples generally require dilution Higher operator training than portable GC
Gas Chromatograph / Mass Spectrometry (GC/MS)	Aromatics and aliphatics, total organic vapor, and chlorinated compounds	0.05 ppb - > 1,000 ppm	3	High sensitivity Consistent measurements Provides the highest quality of speciation	Requires power supply Relatively long analysis time (10 – 60 minutes) Expensive

1A – Qualitative (used to detect general presence of VOCs).

1B – Semi-quantitative (used to approximate total VOC contamination within an order of magnitude).

2 – Quantitative.

3 – Highly quantitative.

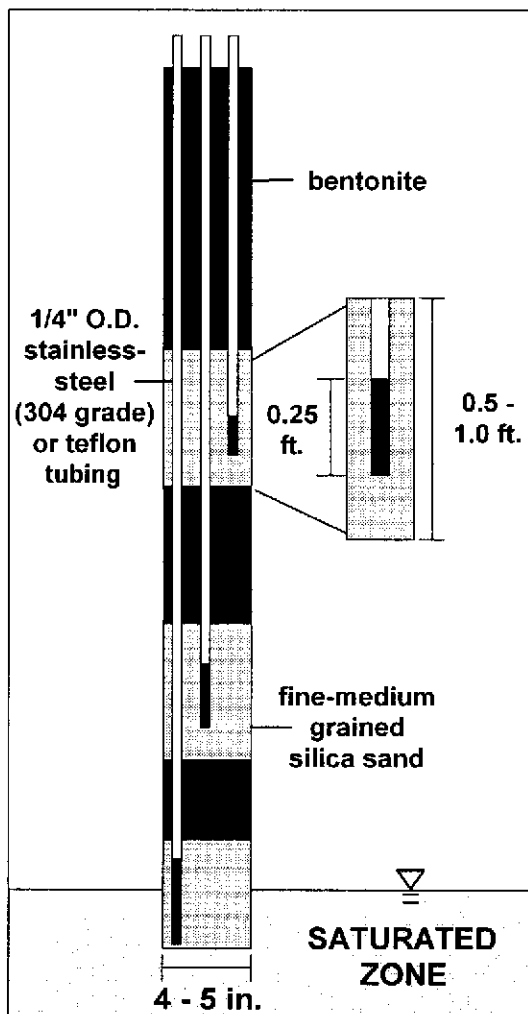


Figure 2. Schematic of vapor-probe nest in augered hole.

installation to allow conditions in the subsurface to reequilibrate.

Phase II: Borehole Development and Soil Sampling

Soil-gas sampling can be achieved from either temporary or fixed sampling locations. Temporary soil-gas sampling is practical for site reconnaissance and field screening, but is not recommended for risk assessment due to the potential for ingress of atmospheric air (dilution). In addition, temporary sampling can conceal temporal variabilities in soil-gas data that are commonly observed at field sites.

- Borehole Development:** Soil-gas probes are can be installed manually by using hand augers or slam bars or mechanically by using rotary augers or direct-push rods (U.S. Environmental Protection Agency, 1997). Manual methods are recommended for probe installation in shallow, unconsolidated vadose zones (< 10 ft.). Mechanical methods are recommended for probe installation in deeper, more consolidated vadose zones or below perched or regional ground-water tables. Use of augers is recommended over direct-push rods for probe installation because augers can create larger diameter boreholes (4 – 5 in.) that can accommodate several additional soil-gas probes (5 - 7) as shown in Figure 2. Regardless of the technique, logging of the borehole (identification of soil layers – depth and thickness) is critical during probe installation so that sampling locations can be properly identified.

- Soil Sampling:** Soil sampling is an essential part of the soil-gas survey. Soil samples should be collected from each distinct (mappable) stratigraphic unit using a stainless-steel soil sampler (barrel, split-spoon, or piston type) that is driven to discrete depths ahead of the auger or direct-push rod. The soil sampler may be driven into the subsurface manually (using a sledgehammer, pneumatic hammer, or slam bar) or mechanically (using a 140 lb. drop hammer attached to a drill rig or Geoprobe®) depending on the vadose-zone thickness, soil type, and degree of consolidation. Each soil sample should be analyzed for:

- bulk density (American Society for Testing and Materials – ASTM D 2937)
- specific gravity (American Society for Testing and Materials – ASTM D 854-92)
- moisture content (American Society for Testing and Materials – ASTM D 2216-90)
- grain size (American Society for Testing and Materials – ASTM D 422-63)
- organic carbon content (American Society for Testing and Materials – ASTM E1195-87(1993))

Bulk density measurements are needed to estimate total porosity, which is used in conjunction with moisture content, to estimate the effective diffusion coefficient, a critical transport parameter (American Petroleum Institute, 1998)¹. Moisture content measurements and grain size measurements (see

¹Effective diffusion coefficients can also be determined experimentally either *in situ* (Kreamer et al., 1988; Johnson et al., 1998) or in laboratory column experiments (Fischer et al., 1996; Batterman et al., 1996).

Table 3. Capillary rise in soils based on grain-size (from Lohman, 1972)

Soil Type	Grain Size (mm)	Capillary Rise (cm)
Fine gravel	5	1.5
Very coarse sand	2	4
Coarse sand	0.5	15
Medium sand	0.3	25
Fine sand	0.15	50
Very fine sand	0.075	100
Coarse silt	0.025	300
Fine silt	0.008	750

Table 3) are used for estimating the thickness of the capillary zone. An accurate estimate of the capillary-zone thickness is important because of the sensitivity of vapor transport to this parameter. Grain-size measurements can also be used to estimate air-phase permeabilities (U.S. Environmental Protection Agency, 1995). Likewise, in-situ techniques, such as Baehr and Hult (1988), can be used to estimate air-phase permeabilities. Organic-carbon content measurements are needed to quantify sorption to vadose-zone soils.

Further discussion of soil boring and sampling techniques is provided in the American Society for Testing and Materials *Standard Guide for Soil Sampling in the Vadose Zone (ASTM D 4700)*.

Phase III: Probe Construction (see Figure 2 and Appendix A)

Soil-gas probes can be constructed out of either 0.125 or 0.25 in. O.D. stainless-steel (grade 304) or teflon tubing that is cut to the desired length, slotted at the base (using a hack saw or power drill), and wrapped with stainless steel or fiberglass screening to avoid potential clogging with soil. Stainless steel or teflon are recommended because of their inert chemical properties. As shown in Figure 2, soil-gas probe nests are constructed by placing the probes in fine-medium grained (clean) silica sand layers separated by layers of bentonite. Bentonite layers (seals) can be prepared in the bore hole by pouring in 2 parts coarse-grained (Easy Seal[®]) bentonite to 1 part water or by injecting a pre-mixed slurry. Each bentonite seal should be pressure tested to avoid short-circuiting (air flow) between probes or the atmosphere. The minimum separation distance between probes is approximately 1 ft; thus, additional boreholes are needed to obtain more fine-scale resolution. Placement of probes below the water

table requires pre-casing to maintain an open borehole during probe installation.

Phase IV: Sample Collection

Active soil-gas sampling is conducted by inducing air flow either manually (by using a gas-tight syringe or hand pump) or mechanically (by using a peristaltic pump or SUMMA[®] canister). Soil-gas samples are collected directly into a sampling container (see Table 4) or from the effluent air stream induced by the sampling pump. Standard operating procedures for SUMMA[®] canister, tedlar bag, and syringe sampling are provided in the Appendices B, C, and D, respectively.

- **Purge and Sample Volumes:** Prior to sample collection, soil-gas probes and auxiliary tubing should be purged with at least 1 system volume. The purge volume should remain consistent for the entire sampling event and should always be reported in field logs. Manual purging using a hand (suction) pump or syringe is preferred over mechanical purging using a vacuum or peristaltic pump because purge volumes can be more accurately controlled, which is especially important when sampling in low permeability soils.
- **Flow Rates:** Flow rates on peristaltic pumps and SUMMA[®] canisters should always be set at a minimum during sample collection to avoid development of significant vacuum pressures (> 10 in. water) which can affect the soil-gas concentration measurement. If vacuum pressures of this magnitude are encountered, sampling should be abandoned or performed periodically at lower flow rates (time integrated). Vacuum pressures should be continuously monitored using pressure gauges arranged in-line (see Appendices B, C, and D), especially in highly saturated or fine-grained, low-permeability soils where higher vacuum pressures can be expected. Vacuum pressures observed during sampling may indicate a clogged or water-saturated probe. Clogged probes can often be unplugged by inserting a small diameter (1/8 in. O.D.) wire down the inside of the probe. Care should be taken, however, to avoid displacing or piercing the screen attached to the base of the soil-gas probe.
- **Sample Containers (see Table 4):** Selection of an appropriate sampling container will depend on the holding time (time between sample collection and analysis) and detection limits. In

general, SUMMA[®] canister and syringe sampling provide more accurate quantification of soil gas concentrations than Tedlar bag sampling and should always be used at sites where low detection levels are desired.

Phase V: Analysis

Various soil-gas analyses are available depending on the survey objectives, budget constraints, and quality assurance/quality control (QA/QC) objectives.

- Analytes:** At LUST sites, VOCs, nitrogen (N₂), O₂, carbon dioxide (CO₂), methane (CH₄), and in some cases, hydrogen sulfide (H₂S) may all be present in soil gas. Their distribution depends on the soil type, stratigraphy, presence of impermeable surface boundaries (e.g., building foundations, asphalt surfaces), and biodegradation. In most risk assessments, identification of the types of VOCs present and their concentration in soil gas is the primary concern. Total VOC concentration data, however, can also be useful for screening level applications. Although not required in most risk assessments, O₂, CO₂, CH₄ and H₂S

concentration data can also provide fundamental biodegradation data to help assess vapor intrusion. In particular, these data can be used to verify biodegradation hypotheses, and estimate biodegradation rates (Lahvis and Baehr, 1996). O₂ and CO₂ concentration data can also be used to map VOC plumes (Kerfoot et al., 1988).

- Analyses:** A comparison of commonly employed field analyses is provided in Table 2. In general, the cost associated with each analysis is proportional to the degree of quantification.
- Methods:** Most soil-gas analyses are performed off-site. The following are approved U.S. Environmental Protection Agency methods for laboratory (off-site) soil-gas analyses:

Analytes	Sample Container	Analysis	EPA Method
organics	canister/tedlar bag	GC	TO-3, 12, 14, 14A
organics	canister	GC/MS	TO-15
organics	sorbent tubes (cartridges)	GC	TO-1, 2, 17
inorganics*	canister/tedlar bag	GC	Method 3C

*O₂, CO₂, N₂, CH₄, and H₂S

Table 4. Comparison of common soil-gas sampling containers (modified from Mayer, 1989)

Type	Application	Sample Volume	Advantages	Limitations
Glass syringe	Collection of samples for on-site GC analysis Suspected concentrations of COC must generally exceed 10 ppb	25-mL	Inert Allows quick, replicate analysis	Holding times are typically short (< 8 hours) Small sample volume Generally unable to detect VOCs at concentrations < 10 ppb
Sorbent trap	Allows for low-concentration measurements (< 10 ppb)	Variable—depends on VOC concentration	Ease of handling Relatively long holding times (days)	Requires precise sample volume (flow) measurements Requires thermal or solvent desorption Soil-gas moisture can affect analysis Provide only qualitative information if used for passive sampling
Tedlar® bag	Collection of samples for delayed analysis (see U.S. Environmental Protection Agency, 1994)	1 – 25 liters	Bulk loss of sample is readily apparent Sample volume measurement not required	Some container materials may contaminate sample Potential for adsorption to bag walls and leakage to atmosphere limits application for risk assessment Containers are not easily reused
Glass bulb	Collection of samples for delayed analysis	2 mL – 2 L	Inert Allows replicate samples	Easily breakable Expensive Leakage through stopcocks and septa possible Short holding times (< 4 hours)
Stainless-steel (SUMMA®) canisters	Collection of samples for delayed analysis (see U.S. Environmental Protection Agency, 1995)	2 mL – 6 L	Inert and durable Longer sample retention times	Expensive Containers not easily reused Can be difficult to decontaminate

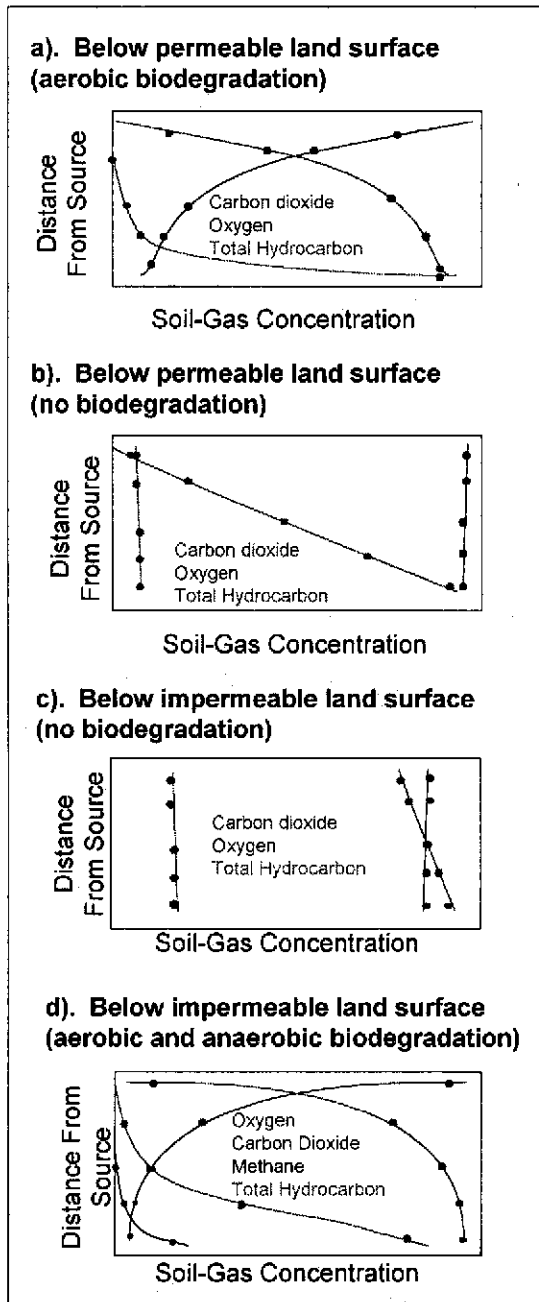


Figure 3. Conceptualization of soil-gas profiles at a petroleum-release site.

- **QA/QC:** QA/QC procedures are an integral part of any soil-gas survey and must be performed to ensure that soil-gas samples are representative of subsurface conditions. The following is a list of some important QA/QC procedures:

- Sampling should be consistent and completed in a relatively short period of time (hours, days) to reduce effects of temperature, barometric pressure, and recharge on soil-gas transport. Holding times and exposure of sampling containers to direct sunlight should be minimized.
- Sampling and drilling equipment should be decontaminated between boreholes to prevent cross contamination.
- All bentonite seals constructed during vapor sampling or probe installation should be pressure tested.
- Soil-gas samples should be collected outside the zone of contamination to assess background concentrations.
- All connections and fittings in the sampling line should be leak checked.
- Field and trip blanks should be used to ensure proper sampling and decontamination procedures. Approximately 1 out of every 10 soil-gas samples should be duplicated to ensure reproducibility of the data.
- Analytical QA/QC should be routinely performed and include: a multi-point calibration curve generated over the range of anticipated soil-gas concentrations, periodic calibration checks, spike samples to determine percent recovery and aid retention time analysis, and sample blanks.

INTERPRETATION AND APPLICATION

Interpretation

The following are important factors to consider in the interpretation of a soil-gas survey:

- Soil gas-concentrations can be relied upon for risk assessment provided the concentration is approximately steady state. The time required to reach steady state increases as the square of the distance from the source. Soil-gas concentrations measured near the source will therefore reach steady state more quickly (hours-days) than concentrations several meters away (weeks to years).
- Regions where soil-gas concentrations increase or decrease sharply should be identified. Steep concentration gradients will exist in fine-grained or wet soils and in areas of significant (aerobic) biodegradation (see Figures 3a and 3d). VOC concentration gradients will be less steep in regions where O_2 is depleted ($< 5\%$) and/or anaerobic biodegradation (as indicated by the presence of CH_4 or H_2S in soil gas) is occurring (Figures 3b, 3c, and 3d). Anaerobic biodegradation is likely to occur in regions, such as, near the source or beneath impermeable barriers, where O_2 concentrations are low ($< 2\%$) and vapor transport is limited.

Table 5. Evaluation of commonly applied models to assess transport in the vadose zone

Model	Type		Processes Considered									
	Analytical	Numerical	Finite Source	NAPL Partitioning	Non-Equilibrium Partitioning	Gaseous-Phase Diffusion	Gaseous-Phase Advection	Ground-water Infiltration	Sorption	Biodegradation	Soil Layering	Variable Moisture
VLEACH (Ravi and Johnson, 1997)		X	X		X	X		X	X		X	X
R-UNSAT (Lahvis and Baehr, 1997)	X	X	X	X		X		X	X	X	X	X
Little et al. (1992)	X					X	X		X			
Farmer et al. (1980)	X					X			X			
Jury et al. (1983)	X		X			X		X	X	X		
Johnson and Ettinger (1991)	X		X			X	X		X		X	
Johnson et al. (1999)	X		X			X	X		X	X	X	

- VOC concentrations in soil gas can not exceed saturated vapor concentrations for sources present above the water table or the vapor-phase equivalent of the aqueous-phase solubility for sources present in ground water (see Table 1). VOC concentrations in soil gas that approach maximum concentrations likely indicate the presence of a non-aqueous phase liquid (NAPL). Note, however, that the maximum soil-gas concentrations can vary significantly depending on source composition, subsurface temperature, and pressure.
- Placing measured soil-gas concentration data along side vertical cross sections of the subsurface can often facilitate interpretation of the soil-gas concentration data.

Application

Although soil gas surveys are beneficial for initial site-assessment (Tier 1) purposes, soil-gas surveys are primarily used in site-specific (Tier 2) evaluations after risk based screening levels (RBSTLs) have been exceeded. For example, soil-gas concentration data can be used to verify indoor-air concentrations, assess long-term vapor intrusion, and establish SSTLs. Transport conditions are assumed to be at or near steady state and biodegradation is typically not considered.

- **Verifying Indoor-Air Concentrations:** According to the American Petroleum Institute (American Petroleum Institute, 1998), indoor-air concentrations are approximately one thousandth of the soil-gas concentration immediately adjacent the building foundation. This relation is consistent with published data from field studies conducted by Nazaroff et al. (1987) on radon-gas intrusion and model results from Johnson and Ettinger (1991). However, there are limitations with this assumption. Near-surface soil-gas concentrations and sub-foundation conditions may differ substantially as a result of varying flow conditions around the building foundation and the potential for short-circuiting (atmospheric contamination) in soil-gas samples collected near land surface.

- **Assessing Long-Term Vapor Intrusion:** Several mathematical models are available for assessing long-term vapor intrusion (see Table 5). Analytical solutions developed by Farmer et al. (1980), Little et al. (1992), Johnson and Ettinger (1991), and Johnson et al. (1999) are most commonly used for this purpose. Transport models developed by Ravi and Johnson (1997), Lahvis and Baehr (1997), Farmer et al. (1980), and Jury et al (1983) can also be used to assess vapor transport, however, these models do not account for gaseous-phase advection, which may be significant at some field sites.

Reliance on near-surface and sub-foundation soil-gas concentrations to assess long-term impacts is not recommended because these concentrations are typically measured several meters away from the source and, consequently, may not have reached steady state. Soil-gas concentrations measured adjacent the source may be more appropriate for assessing long-term impacts, however, this application requires knowledge of the subsurface geology between the source and the receptor.

- **Assessing Site-Specific Target Levels (SSTLs):** Once conditions protective of indoor air (RBSL) have been established, SSTLs can be back-calculated by transport modeling. The SSTL concentration determined by modeling can be directly compared to concentrations in soil gas, or concentrations in soil or groundwater calculated from equilibrium partitioning relations (U.S. Environmental Protection Agency, 1996; American Society for Testing and Materials, 1995).

Other Applications: There are several other applications of soil-gas surveys that are not discussed in this report, which have practical implications for site assessment. These applications include, tracking contaminant plumes in groundwater (Kerfoot, 1988), estimating volatilization rates of hydrocarbon from ground water (Lahvis et al., 1999), predicting mass-loading rates to ground water from sources in the vadose zone (Lahvis and Rehmann, 1999), and quantifying the effectiveness of bioventing applications (Lahvis and Bachr, 1996).

SUMMARY

For soil-gas surveys to be an effective tool in RBCA decision making, care must be taken in the sampling design, sampling process, and, in particular, interpretation of results. Soil-gas survey data should always be supported with site-specific soil and groundwater data as part of a multimedia approach to risk assessment. Lastly, it is important to realize that soil-gas transport is dynamic by nature and may not always be representative of steady-state, long-term conditions.

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REFERENCES

- American Petroleum Institute 1998, Assessing the significance of subsurface contaminant vapor migration to enclosed spaces: Site-specific alternatives to generic estimates, *American Petroleum Institute, Health and Environmental Sciences Department, Publication Number 4674*, December, 1998, pp. 44.
- American Society for Testing and Materials, 1990, Test method for laboratory determination of water (moisture) content of soil and rock, ASTM D 2216-90, *American Society for Testing and Materials*, West Conshohocken, Pennsylvania, Annual Book of ASTM Standards, v. 04:08.
- American Society for Testing and Materials, 1991, Standard guide for soil sampling from the vadose zone, ASTM D 4700-91, *American Society for Testing and Materials*, West Conshohocken, Pennsylvania, Annual Book of ASTM Standards, v. 04:08.
- American Society for Testing and Materials, 1992, Test method for specific gravity of soil, ASTM D 854-92, *American Society for Testing and Materials*, West Conshohocken, Pennsylvania, Annual Book of ASTM Standards, v. 04:08.
- American Society for Testing and Materials, 1992, Standard guide for soil gas monitoring in the vadose zone, ASTM D 5314-92, *American Society for Testing and Materials*, West Conshohocken, Pennsylvania, Annual Book of ASTM Standards, v. 04:09.
- American Society for Testing and Materials 1993, Standard test method for determining a sorption constant (Koc) for an organic chemical in soil and sediments, ASTM E1195-87(1993), *American Society for Testing and Materials*, West Conshohocken, Pennsylvania, Annual Book of ASTM Standards, v. 04:09.
- American Society for Testing and Materials 1995, Standard test method for density of soil in place by the drive-cylinder method, D 2937-95, *American Society for Testing and Materials*, West Conshohocken, Pennsylvania, Annual Book of ASTM Standards, v. 04:08.
- American Society for Testing and Materials, 1995, Standard guide for risk-based corrective action applied at petroleum release sites, ASTM E 1739-95, *American Society for Testing and Materials*,

- West Conshohocken, Pennsylvania, Annual Book of ASTM Standards, v. 04:09.
- American Society for Testing and Materials, 1996, Standard test method for particle size analysis, ASTM D 422-96, *American Society for Testing and Materials*, West Conshohocken, Pennsylvania, Annual Book of ASTM Standards, v. 04:08.
- Baehr, A.L., and Hult, M.F., 1991, Evaluation of unsaturated zone air permeability through pneumatic tests, *Water Resour. Res.*, 27, 2605-2617.
- Batterman, S., Padmanabham, I., and Milne, P. 1996, Effective gas-phase diffusion coefficients in soils at varying water content measured using a one-flow sorbent-based technique, *Environ. Sci. and Technol.*, 30, 770-778.
- DeVaul, G.E., Ettinger, R.A., Salanitro, J.P., and Gustafson, J.B., 1997, Benzene, toluene, ethylbenzene, and Xylenes (BTEX) degradation in vadose zone soils during vapor transport: First-order rate constants, in, *Proceedings of the 1999 Petroleum Hydrocarbons and Organic Chemicals in Ground Water – Prevention, Detection, and Remediation Conference, November 12-14, Houston, Texas*, Ground Water Publishing Company, Westerville, Ohio, 365-379.
- Farmer, W.J., Yang, M.S., Letey, J., and Spencer, W.F., 1980, Hexachlorobenzene: Its vapor pressure and vapor phase diffusion in soil, *Soil Sci. Soc. Am. J.*, 44, 676-680.
- Fischer, J.M., Baker, R.J., and Baehr, A.L., Determination of vapor-phase diffusion coefficients for unsaturated-zone sediments at Galloway-Township, New Jersey, in U.S. Geological Survey Toxic Substances Hydrology Program – *Proceedings of the Technical Meeting, Colorado Springs, Colorado, September 20-24, 1993*, edited by D.W. Morganwalp and D.A. Aronson, U.S. Geol. Surv. Water Resour. Invest. Rep. 94-4015, 1996.
- Johnson, P.C., Kemblowski, M.W., and Colthart, J.D., 1990, Quantitative analysis for the cleanup of hydrocarbon-contaminated soil by in-situ soil venting, *Ground Water*, 28, 413-429.
- Johnson, P.C., and R.A., Ettinger, 1991, Heuristic model for predicting the intrusion rate of contaminant vapors into buildings, *Environ. Sci. Technol.*, 25, 1445-1452.
- Johnson, P.C., Bruce, C., Johnson, R.L., and Kemblowski, M.W., 1998, In situ measurement of effective vapor phase porous media diffusion coefficients, *Environ. Sci. Technol.*, 32, 3405-3409.
- Johnson, P.C., Kemblowski, M.W., and Johnson, R.L., 1999, Assessing the significance of subsurface contaminant vapor migration to enclosed spaces: Site specific alternatives to generic estimates, *J. of Soil Contamination*, 8, 389-421.
- Jury, W.A., Spencer, W.F., and Farmer, W.J., 1983, Behavior Assessment model for trace organics in soil, I: Model description, *Journal of Environmental Quality*, 12, 568-564.
- Kerfoot, H.B., Mayer, C.L., Durgin, P.B., and D'Lugosz, J.J., 1988, Measurement of carbon dioxide in soil gases for indication of subsurface hydrocarbon contamination, *Ground Water Monitoring Review*, 8, 67-70.
- Kerfoot, H.B., 1988, Is soil-gas analysis an effective means of tracking contaminant plumes in ground water? What are the limitations of the technology currently employed?, *Ground Water Monitoring Review*, 8, 54-57.
- Kreamer, D.K., Weeks, E. P., and Thompson, G.M., 1988, A field technique to measure the tortuosity and sorption-affected porosity for gaseous diffusion of materials in the unsaturated zone with experimental results from near Barnwell, South Carolina, *Water Resour. Res.*, 24, 331-341.
- Lahvis, M.A., and A.L. Baehr, 1996, Estimation of rates of aerobic hydrocarbon biodegradation by simulation of gas transport in the unsaturated zone, *Water Resour. Res.*, 32, 2231-2249.
- Lahvis, M.A., and A.L. Baehr, 1997, Documentation of R-UNSAT, a computer model for the simulation of reactive, multispecies transport in the unsaturated zone, *U.S. Geological Survey Open-File Report 97-630*, 104 pp.
- Lahvis, M.A., Baehr, A.L., and Baker, R.J., 1999, Quantification of aerobic biodegradation and volatilization rates of gasoline hydrocarbons near the water table under natural attenuation conditions, *Water Resour. Res.*, 35, 753-765.
- Lahvis, M.A., and Rehmann, L.C., 1999, Simulation of methyl tert-butyl ether (MTBE) transport to ground water from immobile sources of gasoline

- in the vadose zone, in, *Proceedings of the 2000 Petroleum Hydrocarbons and Organic Chemicals in Ground Water – Prevention, Detection, and Remediation Conference, November 17-19, Houston, Texas*, Ground Water Publishing Company, Westerville, Ohio, 247-259.
- Little, J.C., Daisey, J.M., and Nazaroff, W.W., 1992, Transport of subsurface contaminants into buildings: An exposure pathway for volatile organics, *Environ. Sci. Technol.*, 26, 2058-2066.
- Lohman, S.W. 1972, Ground water hydraulics, *U.S. Geological Survey Professional Paper*, 708, 70 pp.
- Mayer, C.L., 1989, Draft interim guidance document for soil-gas surveying, *U.S. Environmental Protection Agency Environmental Monitoring Systems Laboratory, Office of Research and Development*, Contract Number 68-03-3245, 124 pp.
- Nazaroff, W.W., Lewis, S.R., Doyle, S.M., Moed, B.A., and Nero, A.V., 1987, Experiments on pollutant transport from soil into residential basements by pressure-driven airflow, *Environ. Sci. Technol.*, 21, 459-466.
- Ravi, V., and J.A. Johnson, 1997, VLEACH: A one-dimensional finite difference vadose-zone leaching model, *U.S. Environmental Protection Agency Center for Subsurface Modeling Support*, Ada, Oklahoma, 72 pp.
- Robbins, G.A., Deyo, B.G., Temple, M.R., Stuart, J.D., and Lacy, M.J., 1990, Soil-gas surveying for subsurface gasoline contamination using total organic vapor detection instruments, Part I: Theory and laboratory experimentation, *Ground Water Monitoring Review*, 10, 122-131.
- U.S. Environmental Protection Agency, 1994, Tedlar bag sampling, *U.S. Environmental Protection Agency Environmental Response Team, Standard Operating Procedure 2102*, October 10, 1994, Washington, D.C., 5 p.
- U.S. Environmental Protection Agency, 1995, SUMMA canister sampling, *U.S. Environmental Protection Agency Environmental Response Team, Standard Operating Procedure 1704*, July 27, 1995, Washington, D.C., 8 p.
- U.S. Environmental Protection Agency, 1996, Soil screening guidance: *Technical background document*, EPA 540/R/95/128, May 1996, Washington, D.C., 161 p.
- U.S. Environmental Protection Agency, 1997, Expedited site assessment tools for underground storage tank sites: A guide for regulators, *EPA 510/B/97/001*, March 1997, Washington, D.C.