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

Re: Shell-branded Service Station
Former Shell Service Station
4411 Foothill Boulevard
Oakland, California
SAP Code 135686
Incident #98995746
Agency Site #RO0415

Dear Mr. Wickham:

The attached document is provided for your review and comment. Upon information and belief, I declare, under penalty of perjury, that the information contained in the attached document is true and correct.

If you have any questions or concerns, please call me at (707) 865-0251.

Sincerely,

Denis Brown

Denis L. Brown
Project Manager

CONESTOGA-ROVERS
& ASSOCIATES

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July 27, 2007

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

Re: **Soil Gas Survey and Groundwater Assessment Work Plan**
Former Shell Service Station
4411 Foothill Boulevard
Oakland, California
SAP Code 135686
Incident #98995746
Agency Site # RO0000415

Dear Mr. Wickham:

Conestoga-Rovers & Associates (CRA), prepared this work plan on behalf of Equilon Enterprises LLC dba Shell Oil Products US (Shell) in response to the Alameda County Health Care Services Agency's (ACHCSA's) letter dated May 18, 2007, which requested a work plan to perform further investigations associated with the concentrations of fuel hydrocarbons reported in the groundwater at this site. The May 18, 2007 letter was prepared by the ACHCSA in response to CRA's April 19, 2007 *Site Investigation and First Quarter 2007 Groundwater Monitoring Report,* which documented the findings associated with the installation of four onsite groundwater monitoring wells. The four wells where installed to replace the previously existing onsite wells that were destroyed in July 2005 to accommodate the commercial redevelopment of the site. The proposed scope of work presented in this document complies with Regional Water Quality Control Board (RWQCB) and ACHCSA guidelines.

SITE LOCATION AND DESCRIPTION

The site is a former Shell-branded service station located on the southern corner of the intersection of Foothill Boulevard and High Street in Oakland, California (Figure 1). The former station layout included three first-generation underground storage tanks (USTs) (1958 to 1971), three second-generation USTs (1971 to 1984), three third-generation gasoline USTs (1984 to 2002), a waste oil UST (removed 1992), and four product dispensers (Figure 2). Land use in the vicinity of the site is a mix of commercial and residential, with gasoline service stations occupying the northern and western corners of the intersection. The subject property is currently developed as a strip mall with a variety of commercial and retail uses.

WORK PLAN

In the May 18, 2007 letter, citing the elevated concentrations of total petroleum hydrocarbons as gasoline (TPHg) and benzene, toluene, ethylbenzene, and xylenes (BTEX) reported in the onsite groundwater monitoring wells, the ACHCSA requests that a work plan be submitted to conduct soil vapor sampling at the site to investigate the potential for vapor intrusion to indoor air. The May 18, 2007 letter also requests a work plan to further investigate the offsite downgradient groundwater impacts south and southeast of the site, and offsite in the vicinity of the May 2006 soil boring SB-12 (Figure 2). The requested work plan is presented below.

Technical Rational for Proposed Scope of Work

- The prevailing groundwater flow direction for the area around the site is south-southwest, and the onsite flow direction historically observed is variable between the southeast and southwest.
- Groundwater at the site appears to be semi-confined to confined, with depth to groundwater measured between 6.6 and 7.7 feet below grade (fbg) during the March 2007 groundwater monitoring event.
- Three historical fuel releases have been documented at this site, the most significant of which was the release of an unknown quantity of gasoline that occurred circa 1958 during which time free product was noted in an irrigation well located on the property at 4320 Bond Street (Figure 2). The two other releases documented at this site were a 1997 release from the piping that ran between the USTs and the dispensers closest to High Street, and that associated with the waste oil tank UST removed in 1992.
- Concentrations of TPHg and benzene were reported in all four onsite wells during the March 2007 groundwater monitoring event, with maximum concentrations of each reported at 100,000 micrograms per liter (µg/l) and 32,000 µg/l, respectively, in well S-7.
- Soil vapor probes are proposed to be installed in the vicinity of the onsite commercial and offsite residential buildings for the collection of soil gas samples to evaluate the extent, if any, of vapor migration through site soils and to assess the potential for vapor intrusion to indoor air.
- To assess the offsite downgradient groundwater conditions south and southeast of the site, and in the vicinity of boring S-12, four additional offsite groundwater monitoring wells are proposed.

General Work Tasks

Permits: On behalf of Shell, CRA will obtain access agreements from the owner of the property or properties where new borings are proposed.

Permits: CRA will obtain the required drilling permit(s) from Alameda County Public Works Agency for the borings.

Site Safety Plan: CRA will prepare a comprehensive Site-Specific Safety Plan to protect site workers. The plan will be reviewed and signed by each site worker and kept on the site during field activities.

Utility Clearance: Proposed boring locations will be cleared through USA and by a private utility locating service to verify clearance of each boring from subsurface utilities or other obstructions, prior to drilling. In addition, the first five feet of each boring to be advanced by augers or other mechanical drilling method or equipment, will be cleared to a diameter of 3-inches larger than the lead auger using an air-knife, or by hand augering, to minimize potential damage to underground structures not identified through USA or the utility locating service. Borings which will not exceed a total depth of five feet, as with those associated with the proposed soil vapor probes, will be advanced via hand auger to minimize potential damage to underground structures not identified through USA or the utility locating service.

Specific Work Tasks

Soil Gas Survey and Investigation

Soil Vapor Investigation: In order to evaluate any risk posed by the potential for vapor intrusion from hydrocarbon impacted groundwater to indoor air, CRA will advance 12 soil borings (V-1 through V-12) in the approximate locations shown on Figure 3 for the collection of soil gas samples. Onsite soil vapor borings V-1 through V-9 are proposed at select locations along side the two onsite commercial buildings to assess the potential for vapor intrusion into these two buildings. Onsite soil vapor borings V-10 and V-11 are proposed along the southwest property boundary near a residential building located on that adjacent property to assess the potential of vapor intrusion into this building. And offsite soil vapor boring V-12 is proposed in the backyard of a residential building located on the adjacent property at 4320 Bond Street to assess the potential of vapor intrusion into this building.

The soil borings for the installation of the vapor probes will be installed using a hand auger. Based on the depth of static groundwater measured at this site, the borings will be advanced to approximately 5 fbg.

A soil sample will be collected from each boring at approximately 4.5 to 5 fbg for chemical analyses and will be retained in a steel or brass tube. Each tube 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. A standard two to three week turn-around time will be requested for laboratory results.

Soil Vapor Sampling: Following boring installation, a fixed vapor-sampling point will be installed in each boring using ¼-inch diameter Teflon tubing. Each point will have no greater than 3-inch lengths of screen (either pre-purchased or perforated in the field using a drill and very small bit) attached to the Teflon tubing. The vapor points will be targeted for screening between approximately 4.5 to 4.75 fbg. The bottom of the tubing will be wrapped with stainless steel screening to avoid potential clogging. Teflon tape will be used to secure the screen on the tubing. A clean, fine-grained silica sand filter pack will be installed approximately 3-6 inches below and above the screened interval, followed by a two-inch base of pre-hydrated bentonite pellets. Each probe will then be sealed up to the surface using a traffic-rated well box at grade. No sooner than one week following probe installation, soil vapor samples will be collected from each sampling point in summa canisters according to Shell's vapor sampling protocol (Appendix A). Soil vapor samples designated for chemical analyses will be labeled, entered onto a chain-of-custody record, and placed into a cooler without ice for transport to a State of California certified laboratory for analyses. A 72-hour turn-around time will be requested for laboratory results.

Groundwater Assessment Investigation

Groundwater Investigation: Four offsite groundwater monitoring wells (S-10, S-11, S-12, and S-13) are proposed at the locations shown on Figure 3 to assess offsite groundwater conditions south, southeast, and southwest of the site. Borings S-10, S-11, and S-12 will be drilled using hollow-stem auger (HSA) equipment, and boring S-13 is proposed to be hand augered because of expected limited access to this backyard. All four borings will be converted into groundwater monitoring wells.

A CRA geologist will supervise the drilling and describe encountered soils in the borings using the Unified Soil Classification System and Munsell Soil Color Charts. During the HSA work, soil samples will be collected continuously from 5 fbg to the bottom of the boring for lithologic description. Soil samples will be screened in the field for organic vapors using a photo-ionization detector (PID). Exploratory boring logs will be prepared for each boring. PID measurements will be recorded on the boring logs.

Soil samples designated for chemical analyses will be retained at five-foot intervals, from the soil-groundwater interface, and at changes in lithology from each of the borings in steel, brass, or plastic tubes. The tubes will be covered on both ends with Teflon sheets and plastic end caps. Upon their collection, each soil sample 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 analysis. A standard two week turn-around time will be requested for laboratory results.

Monitoring Well Installation: Groundwater at the site appears to be semi-confined to confined, as indicated by the differences between the depth at which it was first encountered during previous boring advancement and the measured depth in site wells. Based on data from the previous borings at this site and from the existing onsite wells, first encountered water is expected at approximately 11 fbg. Each well screen interval will extend from approximately 5 feet to no more than 10 feet below first-encountered groundwater, depending on lithology. The final screen length will be determined based of field conditions. Each well will be constructed using 2-inch diameter Schedule 40 PVC casing using a screen slot size of 0.010 and a #2/12 filter pack, or similar. The filter pack in each well will be placed to 2 feet above the top of the well screen followed by a thick bentonite seal and cement grout to grade. Actual well construction details will be based on field conditions encountered during drilling. Each well will be secured with a locking cap under a traffic-rated well box.

Well Development and Sampling: At least 48-hours after their installation, Blaine Tech Services, Inc. (Blaine) of San Jose, California will develop the new wells. The sampling of the wells will be performed in conjunction with the sampling of the existing wells during the subsequent quarterly sample event after the wells are installed, in accordance with the established monitoring program for the site

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. The information will be uploaded into the State of California Geo-Tracker database, as required.

CHEMICAL ANALYSIS

Groundwater and select soil samples will be analyzed for total petroleum hydrocarbon as diesel (TPHd) by EPA Method 8015M with single silica gel cleanup, for TPHg by EPA Method 81015M, and for BTEX and the oxygenates methyl tertiary butyl ether (MTBE), tertiary butyl alcohol (TBA), di-isopropyl ether, ethyl tertiary butyl ether, and tertiary amyl methyl ether, and 1,2-dichloroethane and ethylene dibromide, by EPA Method 8260B.

Soil vapor samples will be analyzed for total petroleum hydrocarbons (middle distillates), TPHg, BTEX, MTBE, and TBA by Methods TO-3 and/or TO-15, with appropriate tracer gas compounds.

REPORT PREPARATION

Following the receipt of analytical results from the laboratory, CRA will prepare a written report which will include a description of the field procedures, a presentation of the analytical results, tabulated data, figures showing sample locations, the complete analytical laboratory reports, boring logs with well construction details, and findings. The groundwater monitoring data will be incorporated into the subsequent Quarterly Monitoring Report.

CERTIFICATION

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

SCHEDULE

CRA is prepared to begin work upon approval of this work plan by ACHCSA.

CLOSING

If you have any questions regarding the contents of this document, please call Dennis Baertschi at (707) 268-3813

Sincerely,
Conestoga-Rovers & Associates

Dennis Baertschi
Project Geologist

Ana Friel

ANA FRIEL
No. 6452
exp 9/07

Ana Friel, PG
Associate Geologist

Figures:
1. Vicinity Map
2. Site Map
3. Proposed Monitoring Well and Vapor Probe Location Map

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

cc: Denis Brown, Shell Oil Products US
Bill Phua, c/o Jay Phares, 10700 MacArthur Blvd., Suite 200, Oakland, CA 94605-5260, Attention: HK Phares

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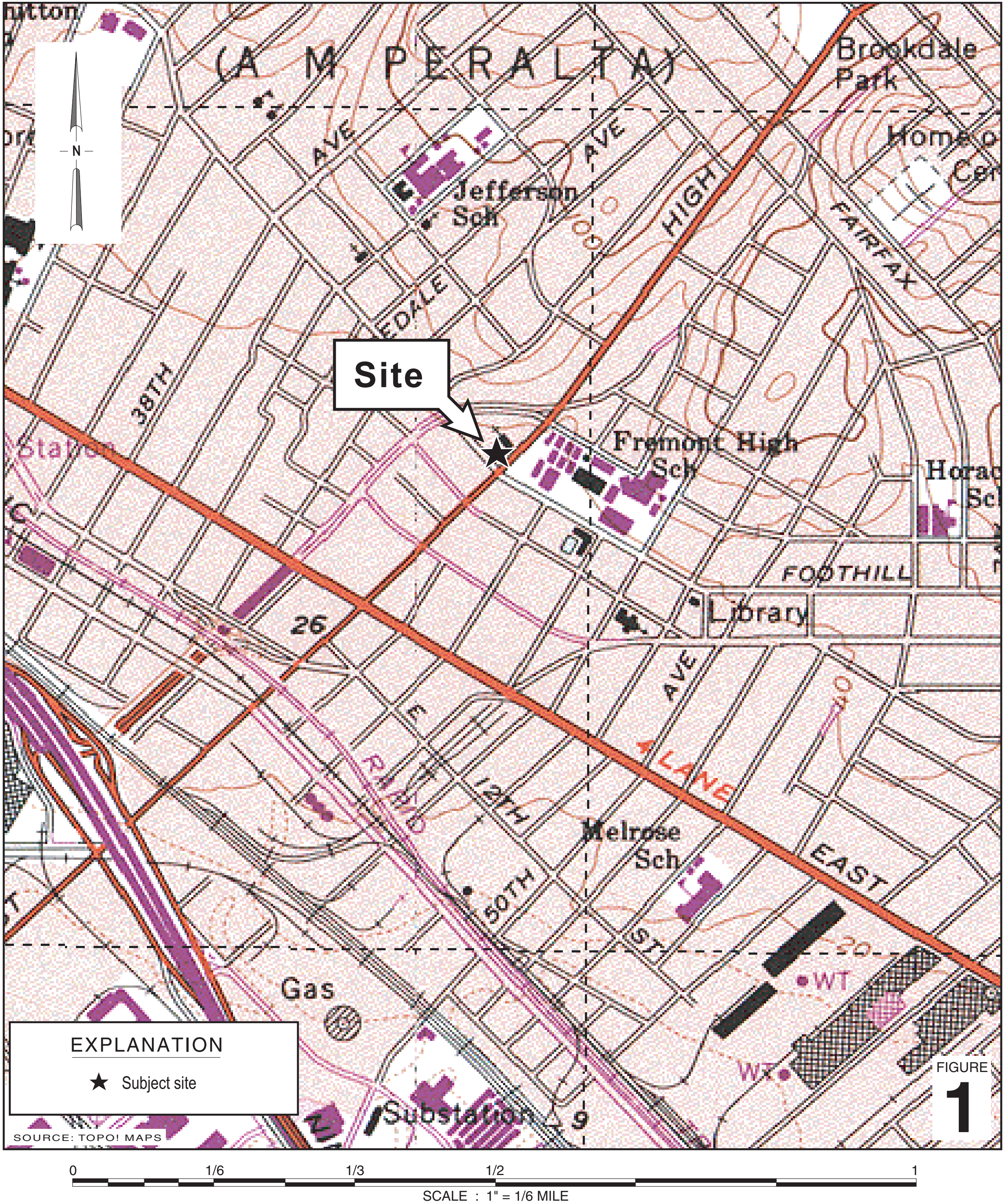

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Former Shell Service Station

4411 Foothill Boulevard
Oakland, California
Incident #98995746

CONESTOGA-ROVERS
& ASSOCIATES

Vicinity Map

9-Feb-07

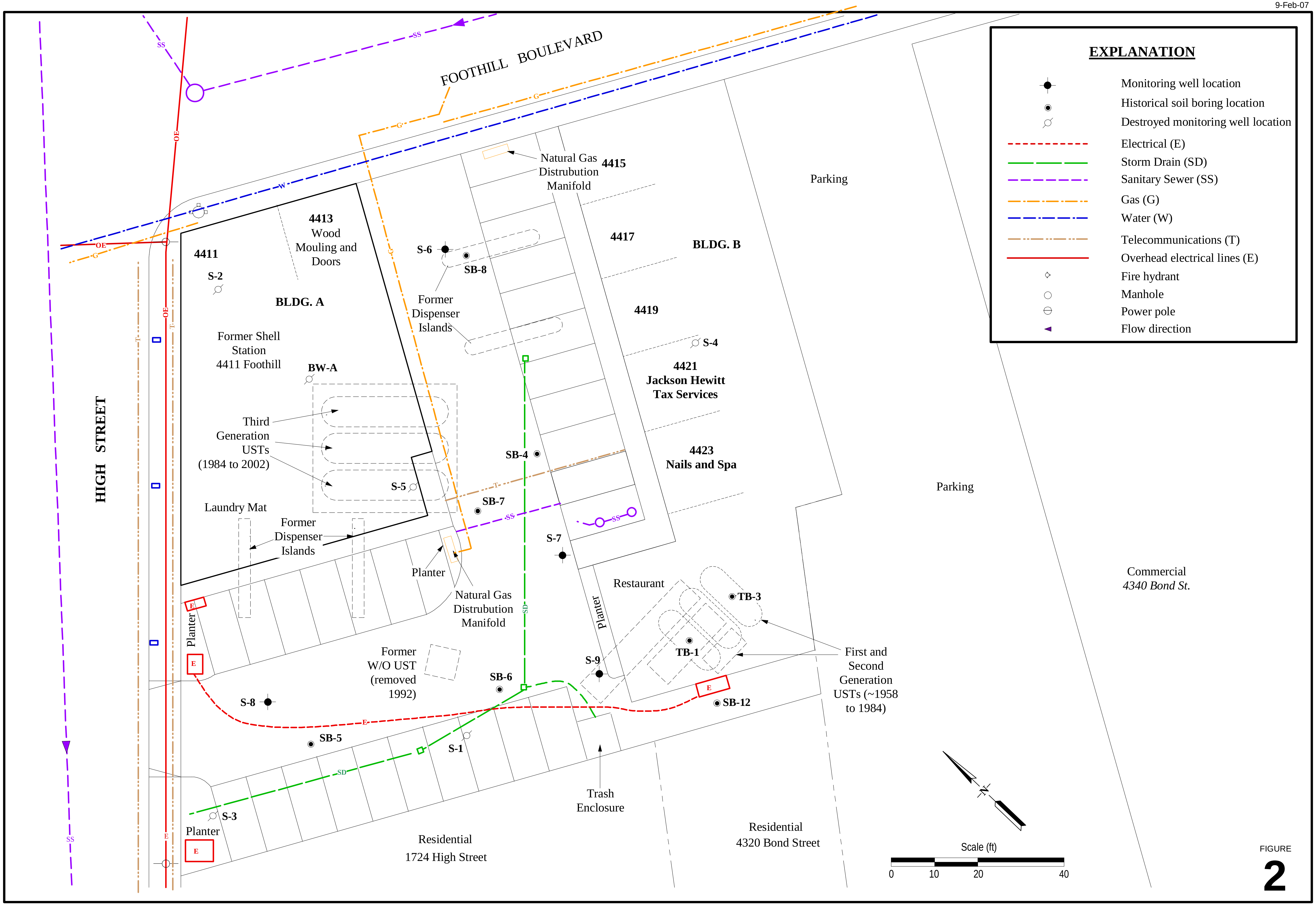

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FIGURE

2

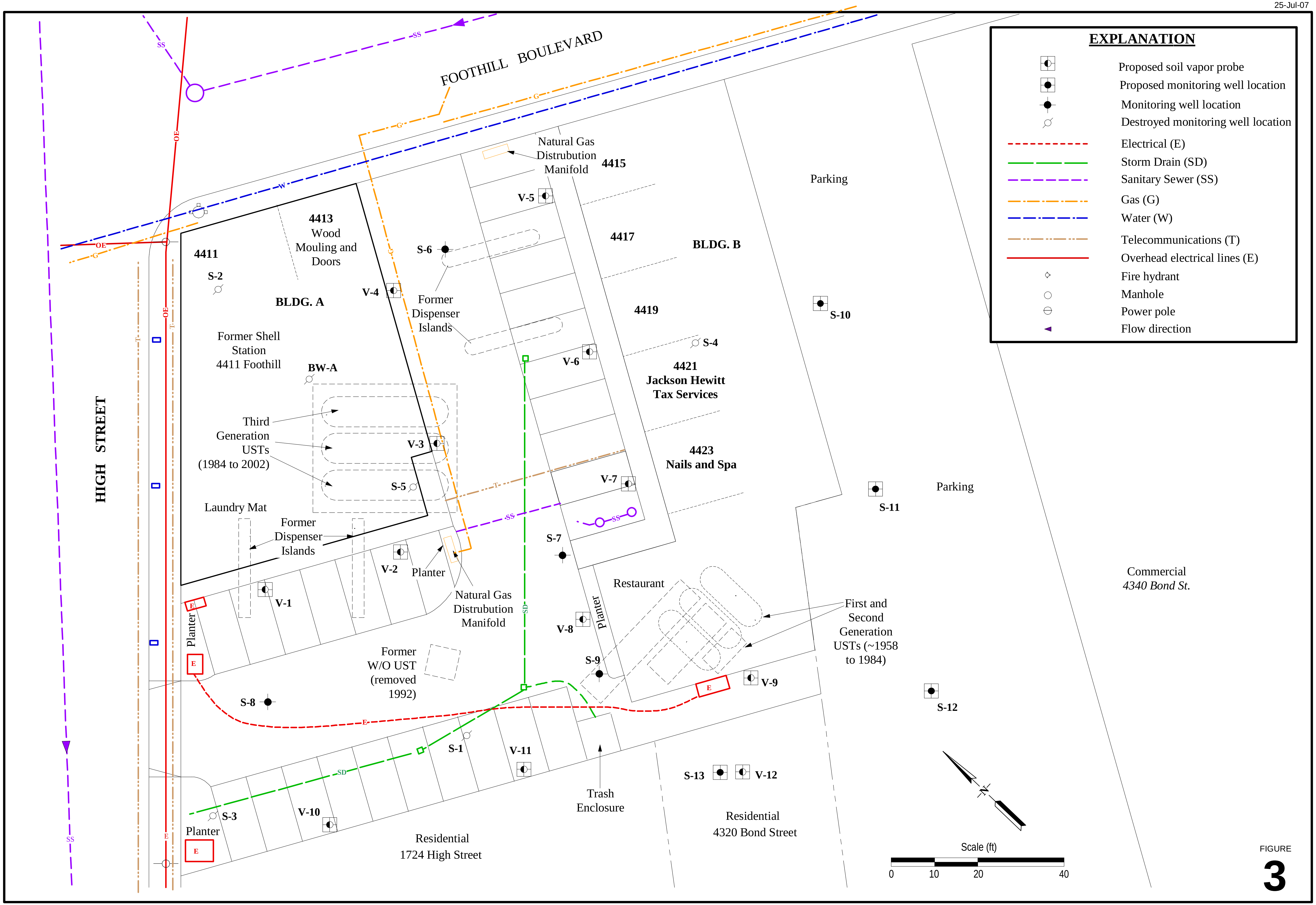
Site Map

Former Shell Service Station

4411 Foothill Boulevard
Oakland, California

25-Jul-07

Proposed Monitoring Well and Vapor Probe Location Map



FIGURE

3

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Former Shell Service Station

4411 Foothill Boulevard
Oakland, California

APPENDIX A

Shell's Guidance on Use of Soil-Gas Surveys to Assess Vapor Transport to Indoor Air

Shell Global Solutions

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

Report Prepared by:

Shell Global Solutions (US) Inc.
Matthew A. Lahvis

07 October 2002

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FIGURES

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.
- Tier 2 and Tier 3 (site-specific) evaluations
  - to validate or predict indoor-air concentrations,
  - to quantify rates of vapor intrusion and
  - to establish site-specific target levels (SSTLs)
  - to verify biodegradation hypotheses.

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-.*

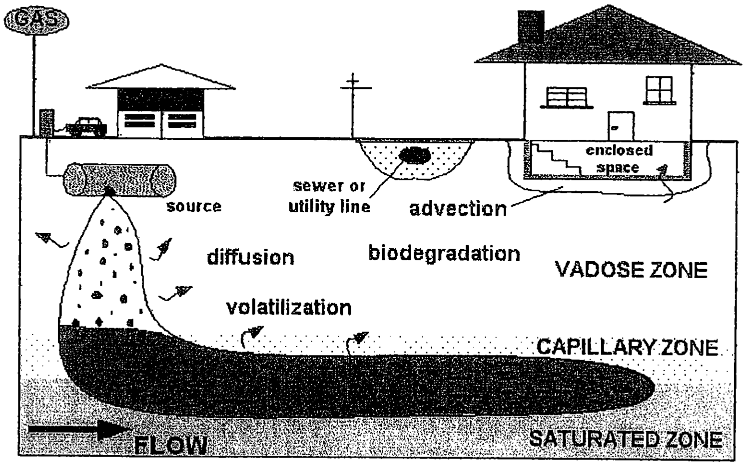

Figure 1. Conceptualization of vapor transport to indoor air at a LUST site.

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

Compound	Pure Component Water Solubility (mg/L)	Henry's Law Constant (unitless)	Saturated Vapor Concentration (mg/m^3)	Maximum Concentration in Soil Gas (mg/m^3)	Maximum Concentration in Soil Gas Based on Target Indoor Air Concentration (mg/m^3)
benzene	1.75E+03	2.28E-01	4.0E+05	5.2E+03 [1]	1.3E-01
toluene	5.26E+02	2.72E-01	1.4E+05	2.8E+04 [1]	4.0E+01
ethylbenzene	1.69E+02	3.23E-01	5.5E+04	1.7E+03 [1]	1.0E+02
o-xylene	1.78E+02	2.13E-01	3.8E+04	3.8E+02 [1]	7.0E+02
trichloroethylene	1.10E+03	4.22E-01	4.6E+05	4.6E+05	5.9E-01
1,1 dichloroethylene	2.25E+03	1.07E+00	2.4E+06	2.4E+06	2.0E-02
1,1,1 trichloroethane	1.33E+03	7.05E-01	9.4E+05	9.4E+05	1.0E+02
1,1,2,2 tetrachloroethylene	2.00E+02	7.54E-01	1.5E+05	1.5E+05	1.7E-02

[1] Concentration in equilibrium with gasoline having the following mole fraction composition for gasoline: benzene – 1.3%, toluene -- 20%, ethylbenzene --3%, and o-xylene – 1%.

[2] Target concentration calculated by assuming a risk level = 10^{-5}, a hazard index = 1, and a soil gas to indoor air attenuation coefficient = 0.01.

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 -- O_2), 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: Probe Construction and Installation,
- Phase III: Soil Sampling,

- Phase IV: Soil-Gas Sampling, and
- Phase V: Analysis.

Phase I: Method Selection and Sampling Design

The two principal methods applied in soil-gas sampling are active and passive. Selection of the appropriate method depends on 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 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 cannot be directly measured.

- *Vertical Sampling:* The design of a soil-gas sampling network requires fundamental knowledge of source location, soil stratigraphy, and potential exposure pathways. These data are often determined through reconnaissance soil and soil-gas sampling using a Geoprobe® and on-site soil-gas analysis (see Table 2). Placing soil-gas probes between the source (soil or ground-water plume) and the receptor (building foundation) provides a means to assess the vapor pathway. A minimum of 2 soil gas probes is needed to define a concentration gradient and the direction of the source. In general, more probes are needed, however, to evaluate perturbations in the soil-gas distribution caused by heterogeneities in the transport properties of unsaturated-zone soils. It is often advantageous to maximize the number of soil-gas probes within a given nest because they can be installed without much additional cost and effort. In general, soil-gas probes should be positioned near areas of concern (source, receptor) to validate pathway assumptions. In addition, it is often beneficial to place soil-gas probes in regions where sharp soil-gas concentration gradient tend to develop, such as near the water table (for sources in ground water) or just above or below fine-grained soil layers. Soil-gas probes should also be placed in higher-permeability units that may serve as preferential pathways for vapor migration. This approach requires greater effort and expense than fixed-interval installation because the presence, thickness, and depth of target soil horizons, needs to be known *apriori*. Boring logs and site plans should always be evaluated to identify soil strata, perched water and clay lenses, buried structures, and recently disturbed soils or backfills.

  Placement of 1 or 2 soil-gas probes below the water table can also be beneficial at sites where a ground-water source is present. These probes can provide more accurate water-table concentration data than can be obtained through conventional monitoring wells that are typically screened over much greater lengths (2 – 20 ft). These probes can also provide additional soil-gas data during periods when the water-table elevation is low.

- *Areal Sampling:* Areal spacing of soil-gas probes depends on the purpose of the soil-gas investigation. For general mapping purposes, probe nests are spaced rather sparsely (e.g., 15 to 30 ft apart), usually along a grid pattern. Probe nests are spaced at closer intervals (e.g., 3 to 10 ft apart) when targeting identified exposure pathways, such as building foundations, storage tanks, and transfer conduits (e.g., sewer lines, trenches, utility vaults, pipelines and other preferential pathways). In addition, installation of two or more probe nests in close proximity can provide confirmatory data, which may be beneficial, even at sites where the vapor pathway is considered well defined.

- *Chronic Sampling:* Temporal effects that occur as a result of changes in barometric pressure, water-table elevation, moisture content, source composition, recharge, biodegradation, can affect the distribution of VOCs in soil-gas over time. Depending on the chemical compound, soil type, distance from the source, and relative age of the release, response and equilibration times can range from hours to years. Chronic sampling at fixed locations provides a means to assess these temporal variabilities. The equilibration time should also be accounted for in determining the

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 Chromotograph / Mass Spectometry (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.

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

commencement of soil-gas sampling following probe installation. In general, 3 to 4 weeks should be allowed for re-equilibration.

Phase II: Soil Sampling

Soil sampling is an essential component of any soil-gas survey. Soil sampling can be used to locate potential sources in soil as well as soil units that may serve as potential barriers or conduits for soil-gas migration. Soil samples should be collected from each distinct (mappable) stratigraphic unit using a stainless-steel soil sampler (barrel, split-spoon, or piston type) attached to 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 drop hammer attached to a drill rig or Geoprobe®. Method selection will depend on the vadose-zone thickness, soil type, and degree of consolidation. Soil samples should be field screened using a portable PID or FID to locate sources. Remaining sections of the core should be analyzed for the following soil properties:

- 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 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 and Installation

- *Probe Construction:* Soil-gas probes can either be bought commercially (implants) or be constructed by hand using 1/8 – 1/4 in. O.D. stainless-steel (grade 304) or teflon tubing. Stainless steel and teflon are recommended because of their inert chemical properties and low potential for adsorption. A small tubing diameter is recommended to minimize purge requirements, especially when sampling in fine-grained soils where the soil-gas flow rate is limited.

- *Installation:* Soil-gas surveys can be conducted 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 inability to assess temporal variability. Temporary probes installed in coarse-grained or hard pan soils may also be susceptible to entrainment (flow) of soil gas or atmospheric air along probe walls provided tight contact between the probe and soil is not achieved. For these reasons, fixed sampling is generally recommended for risk assessment. Soil-gas probes can either 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 preferable for probe installation in deeper, more consolidated vadose zones or below perched or regional ground-water tables. Direct-push methods will yield small

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[1] Effective 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).

diameter boreholes (< 2 in.) that, in general, accommodate only a few (1 – 2) soil-gas probes. Augers typically create larger diameter (>4 in.) boreholes that can accommodate several soil-gas probes. Use of augers is recommended in fine-grained soils (e.g., silts, clays) because direct-push techniques can result in blockage of pore space along borehole walls during operation. This restriction can increase the potential for short-circuiting to the atmosphere (i.e., sample dilution) during soil-gas sampling. As shown in Figure 2, soil-gas probes should be nested in fine-medium grained (clean) silica sand layers and separated by layers (seals) of bentonite. The bentonite seals should be pressure tested to avoid short-circuiting (air flow) between probes or the atmosphere. The minimum separation distance between probes is generally 6 to 12 inches depending on the length of the screened interval (see Figure 2). Additional boreholes are therefore necessary if finer-scale resolution is desired. If using an auger, pre-casing is required to install probes below the water table.

Phase IV: Soil-Gas Sampling

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. The EPA has issued standard operating procedures for SUMMA® canister (SOP #1704, U.S. Environmental Protection Agency, 1995) and tedlar bag (SOP #2102, U.S. Environmental Protection Agency, 1994) sampling.

- *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) that 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, 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. Inserting a small diameter (1/8 in. O.D.) wire down the

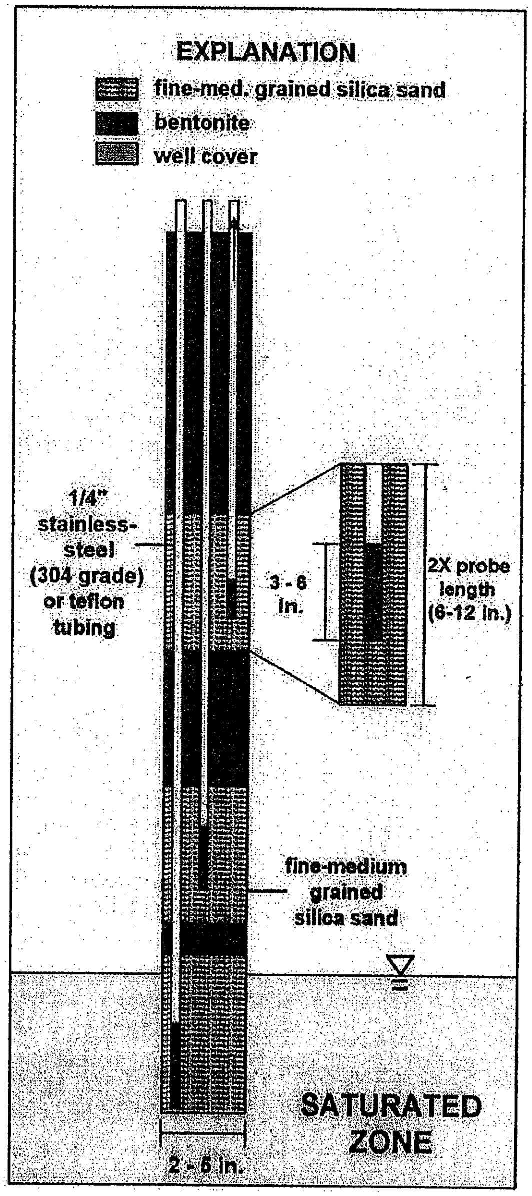

Figure 2. Schematic of vapor-probe nest in augered hole.

inside of the probe can often times unplug a clogged 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 (N_2), O_2, carbon dioxide (CO_2), methane (CH_4), and in some cases, hydrogen sulfide (H_2S) 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, O_2, CO_2, CH_4 and H_2S 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). O_2 and CO_2 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.

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

*O_2, CO_2, N_2, CH_4, and H_2S

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 should 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

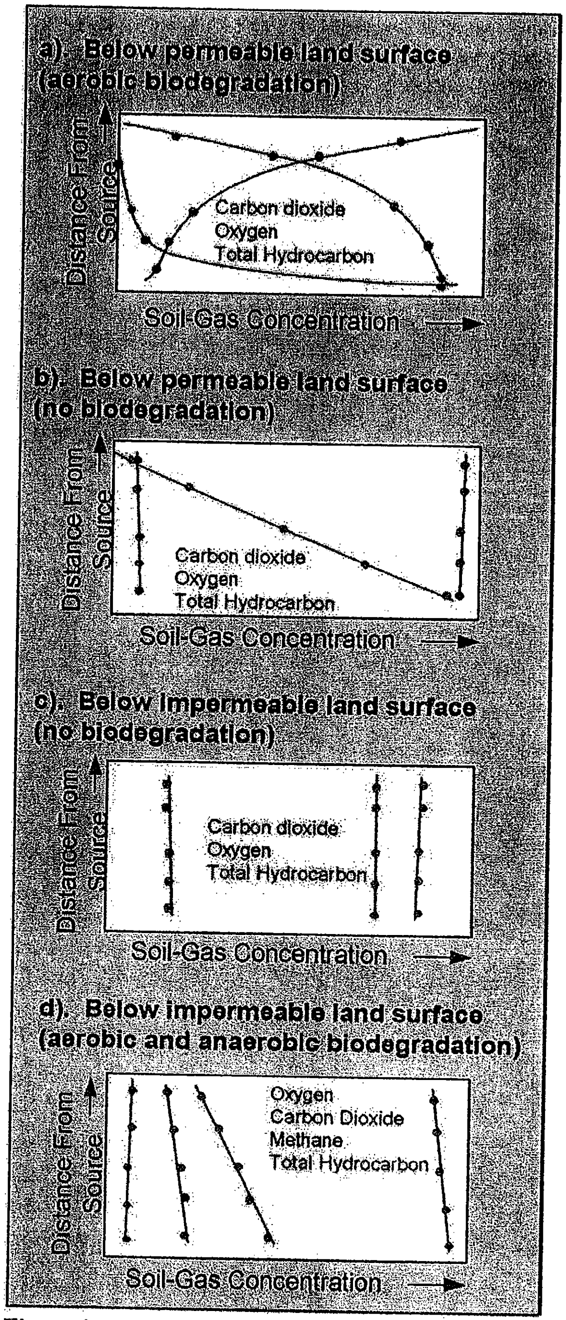

Figure 3. Generalization of soil-gas profiles at a petroleum-release site.

- *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:

- *QA/QC:* QA/QC procedures are an integral part of any soil-gas survey and should 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.

– Ask lab for ideas on leak detection compound.

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%), an

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	

impermeable barrier exists at land surface, 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.

- VOC concentrations in soil gas cannot 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). Maximum concentrations in soil gas can, however, vary significantly depending on source composition, subsurface temperature and pressure, and other temporal phenomena.

- 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 and Tier 3) evaluations after risk based screening levels (RBSLs) 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 Baehr, 1996).

SUMMARY

For soil-gas surveys to be an effective tool in RBCA decision making, care should 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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