

Collecting and Interpreting Soil Gas Samples from the Vadose Zone

A Practical Strategy for Assessing the Subsurface Vapor-to-Indoor Air Migration Pathway at Petroleum Hydrocarbon Sites

Regulatory Analysis and Scientific Affairs

PUBLICATION NUMBER 4741
NOVEMBER 2005

Copyright American Petroleum Institute
Reproduced by IHS under license with API
No reproduction or networking permitted without license from IHS

Collecting and Interpreting Soil Gas Samples from the Vadose Zone

A Practical Strategy for Assessing the Subsurface Vapor-to-Indoor Air Migration Pathway at Petroleum Hydrocarbon Sites

Regulatory and Scientific Affairs

PUBLICATION NUMBER 4741
NOVEMBER 2005

PREPARED UNDER CONTRACT BY:
Lesley Hay Wilson, Ph.D.
Sage Risk Solutions LLC

Paul C. Johnson, Ph.D.
Department of Civil and Environmental Engineering
Arizona State University

James R. Rocco
Sage Risk Solutions LLC

SPECIAL NOTES

API publications necessarily address problems of a general nature. With respect to particular circumstances, local, state, and federal laws and regulations should be reviewed.

Neither API nor any of API's employees, subcontractors, consultants, committees, or other assignees make any warranty or representation, either express or implied, with respect to the accuracy, completeness, or usefulness of the information contained herein, or assume any liability or responsibility for any use, or the results of such use, of any information or process disclosed in this publication. Neither API nor any of API's employees, subcontractors, consultants, or other assignees represent that use of this publication would not infringe upon privately owned rights.

API publications may be used by anyone desiring to do so. Every effort has been made by the Institute to assure the accuracy and reliability of the data contained in them; however, the Institute makes no representation, warranty, or guarantee in connection with this publication and hereby expressly disclaims any liability or responsibility for loss or damage resulting from its use or for the violation of any authorities having jurisdiction with which this publication may conflict.

API publications are published to facilitate the broad availability of proven, sound engineering and operating practices. These publications are not intended to obviate the need for applying sound engineering judgment regarding when and where these publications should be utilized. The formulation and publication of API publications is not intended in any way to inhibit anyone from using any other practices.

API is not undertaking to meet the duties of employers, manufactures, or supplies to warn and properly train and equip their employees, and others exposed, concerning health and safety risks and precautions, nor undertaking their obligations to comply with authorities having jurisdiction.

Information concerning safety and health risks and proper precautions with respect to particular materials and conditions should be obtained from the employer, the manufacturer or supplier of that material, or the material safety data sheet.

All rights reserved. No part of this work may be reproduced, stored in a retrieval system, or transmitted by any means, electronic, mechanical, photocopying, recording, or otherwise, without prior written permission from the publisher. Contact the Publisher, API Publishing Services, 1220 L Street, N.W., Washington, D.C. 20005.

Copyright © 2005 American Petroleum Institute

FOREWORD

Nothing contained in any API publication is to be construed as granting any right, by implication or otherwise, for the manufacture, sale, or use of any method, apparatus, or product covered by letters patent. Neither should anything contained in the publication be construed as insuring anyone against liability for infringement of letters patent.

Suggested revisions are invited and should be submitted to the Director of Regulatory Analysis and Scientific Affairs, API, 1220 L Street, NW, Washington, DC 20005.

The information included in this publication is intended as general guidelines and not specific recommendations for all sites. Site-specific considerations, professional judgment and regulatory requirements will dictate the methods and procedures used at any particular site. This publication is not intended to replace the advice of qualified professionals.

Trademarks:

Cali-5-bond[®] is a registered trademark of Calibrated Instruments, Inc.

Luer-lok[®] is a registered trademark of the Becton, Dickinson and Company Corporation

Tedlar[®] is a registered trademark of the E. I. Du Pont De Nemours and Company Corporation

Teflon[®] is a registered trademark of the E. I. Du Pont De Nemours and Company Corporation

Tenax[®] is a registered trademark of the Buchem B.V. Corporation

Acknowledgements

API and the authors would like to acknowledge and thank the following people for their contributions of time, comments, and expertise during this study and in the preparation of this report:

API STAFF CONTACT

Harley Hopkins, Regulatory Analysis and Scientific Affairs Department (RASA)

MEMBERS OF THE SOIL AND GROUNDWATER TECHNICAL TASK FORCE

Curtis Stanley, Shell Global Solutions (U.S.), Chairman

Brian Davis, Chevron Corporation

Rick Greiner, ConocoPhillips

Dan Irvin, ConocoPhillips

Vic Kremesec, Atlantic Richfield Company, A BP Affiliated Company

Matt Lahvis, Shell Global Solutions (U.S.), Inc.

Paul Lundegard, Chevron Corporation

Mark Malander, ExxonMobil Corporation

Tom Peargin, Chevron Corporation

Todd Ririe, Chevron Corporation

OUTSIDE REVIEWERS

Bart Eklund, URS Corporation

Robert Ettinger, GeoSyntec Consultants

Blayne Hartman, H&P Mobile Geochemistry

Robert Pirkle, Microseeps

Gina M. Plantz, Severn Trent Laboratories, Inc.

Chris VanCantfort

Executive Summary

This document focuses on the collection of soil gas samples for assessing the significance of the subsurface-vapor-to-indoor-air exposure pathway. While soil gas collection is not the only means of assessing this pathway, soil gas data play a prominent role in recent guidance published by the American Petroleum Institute (API 1998) and the United States Environmental Protection Agency (USEPA 2002a). For example, these data can be used to help make decisions concerning:

- Resource Conservation and Recovery Act (RCRA) corrective action environmental indicators (EI) for human health exposures
- Current exposure scenarios in existing buildings
- Future exposure scenarios in existing buildings
- Future exposure scenarios in future buildings.

This document is intended to complement API 1998 and USEPA 2002a. It provides more in-depth information on issues associated with soil gas sampling and data interpretation as applied to pathway assessment. This document is specifically focused on petroleum hydrocarbon impacted sites. However, much of the information presented is applicable to all soil gas sampling. Soil gas sampling has been used for many years for site assessment and remediation system monitoring purposes. The user, however, will find that the data quality objectives and acceptable methods of sampling for pathway assessment are different from those that are commonly acceptable for using soil gas data for delineation, site assessment, or monitoring remediation systems.

This document is unique in that it emphasizes conceptual models for vapor transport, describes how to choose sample locations and depths, explains how to check the data for inconsistencies and also provides checklists on each of these topics to assist field project managers. This document allows for flexibility in the selection and refinement of practicable and defensible sampling methods. The focus here is on identifying key issues associated with soil gas sampling and data interpretation.

Field project managers should find this document useful when developing scope-of-work requirements for site-specific work plans and bid requests. To support preparation of site-specific work plans, scope-of-work action items are included at the end of Sections 4.0 through 7.0.

Section 1.0 provides a brief introduction. Section 2.0 discusses soil gas transport, with emphasis on petroleum hydrocarbon vapors, and presents a brief synopsis of expected soil gas profiles based on empirical analysis of existing data. Section 3.0 discusses the conceptual vapor-migration model. Section 4.0 focuses on sampling locations, depths, and sampling frequency. Section 5.0 focuses on monitoring installations and sample collection procedures. Section 6.0 discusses methods of soil gas analysis. Section 7.0 discusses interpretation of soil gas data. Appendix A provides a site information checklist. Appendix B provides worksheets for three typical scenarios that can be used for planning sampling locations. Appendix C provides more details on sample collection. Appendix D gives supporting information on analytical methods, and Appendix E provides tools to be used in the data evaluation.

Recommendations presented here are based on the experience and professional judgment of the authors and are designed to be broadly applicable. This does not imply that the recommendations are universally applicable or that there are not situations for which other methods or procedures would be better suited. The user of this manual is cautioned to consider all of the site-specific information and to make decisions based on site-specific circumstances, experience, and professional judgment. In addition, some regulatory agencies have expressed preferences for sampling methods and techniques. The applicable regulatory preferences should be examined for each site.

This document does not address all potential strategies for assessing the vapor-to-indoor-air pathway. The user of this manual is directed to USEPA 2002a, and applicable state regulatory guidance for other methods to assess the vapor-to-indoor-air pathway (see PaDEP 2002; MaDEP 2002; WDHFS 2003; NJDEP 2004; CRWQCB 2003; CSDDEH 2003).

This document also does not address safety- and hazard-mitigation efforts to prevent fires or explosions resulting from the accumulation of hazardous vapors. It assumes that these situations have been controlled by emergency or immediate response actions before the planning of a soil-gas-sampling program is initiated. If the results of the soil-gas-sampling program indicate that there is an immediate concern for human exposures to vapor-phase chemicals of concern, then emergency response or interim actions should be implemented as required under state or federal regulations.

Contents

1.0	Introduction	1
2.0	Soil Gas Transport and Soil Gas Profiles at Petroleum Hydrocarbon Impacted Sites.....	3
2.1	Expectations for Soil Gas Profiles at Petroleum Hydrocarbon Impacted Sites	5
2.2	Measured Soil Gas Profiles at Petroleum Hydrocarbon Impacted Sites.....	7
3.0	Conceptual Migration Model for Subsurface Vapor to Indoor Air.....	14
4.0	Development of a Strategy for Soil Gas Sampling.....	17
4.1	General Approach.....	18
4.2	Point Sampling	18
4.3	Transects and Vertical Profiles.....	19
4.3.1	Selection of Lateral Positions for Soil Gas Transects.....	21
4.3.2	Vertical Profiles.....	22
4.4	Summary of Sampling Depth and Location Selection Considerations.....	24
4.5	Some Comments on Sample Collection Adjacent to and Beneath Buildings.....	29
4.6	Sampling Frequency.....	31
4.7	Additional Considerations to Increase Confidence in Data Sets and the Interpretation of Soil-Gas-Sampling Results.....	32
5.0	Soil Gas Sample Collection.....	35
5.1	Basic Monitoring Installation Options.....	35
5.1.1	Permanent Probes	36
5.1.2	Temporary Driven Probes.....	37
5.2	Comparison of Monitoring Installations.....	37
5.3	Other Considerations for Sampling Probe Installations.....	39
5.4	Sample Collection Procedures.....	39
5.4.1	Soil Gas Equilibration	39
5.4.2	Sample Probe Purging	40
5.4.3	Sample Collection.....	40
5.4.4	Sample Collection Vacuum.....	40
5.5	Ways to Avoid Common Problems with Soil Gas Sampling	41
5.6	Alternatives to Soil Gas Sampling.....	43
5.6.1	Passive Implant Samplers.....	43
5.6.2	Flux Chambers.....	44
6.0	Analytical Methods	46
6.1	Analytical Method Selection	46
6.1.1	Field Analytical Methods	48
6.1.2	Common Analytical Methods.....	48
6.2	Data Quality.....	48
7.0	Analysis and Interpretation of Soil Gas Sampling Data	50
7.1	Data Organization.....	52
7.2	Data Analysis.....	53
7.2.1	Data Quality Analysis.....	53
7.2.2	Data Consistency Analysis	54
7.3	Exposure Pathway Assessment.....	55
7.3.1	Exposure Pathway Completeness	55
7.3.2	Exposure Pathway Significance.....	56
7.4	Further Evaluation	56
8.0	References	58
9.0	Additional Reading.....	61
9.1	Analytical Methods.....	61
9.2	Biodegradation	61
9.3	Data Analysis.....	62
9.4	General	62
9.5	Modeling	63
9.6	Sample Collection Methods.....	64
9.7	Site Characteristics and Conceptual Vapor-Migration Models	65

Appendix A.	Characteristics Checklist
Appendix B.	Selection of Soil Gas Sample Locations
Appendix C.	Soil Gas Sample Collection
Appendix D.	Analytical Methods
Appendix E.	Data Evaluation

Figures

Figure 2-1.	Typical conventional conceptual model of soil gas migration.....	3
Figure 2-2.	Revised conceptual model of soil gas migration at petroleum hydrocarbon impacted sites.....	5
Figure 2-3.	Soil gas profiles (Roggemans et al. 2002).	9
Figure 2-4.	Soil gas profile at a site with methane production in the source zone (Johnson et al. 2003). This figure shows the soil gas profiles for oxygen (circles) and methane (diamonds).	10
Figure 2-5.	Normalized soil gas concentration distribution for oxygen and hydrocarbon undergoing aerobic biodegradation with first-order rate $\lambda = 0.18 \text{ (h}^{-1}\text{)}$ and vapor source at concentrations of 20 mg/L, 100 mg/L and 200 mg/L located underneath a basement foundation at a depth of 8 m below ground surface. Hydrocarbon and oxygen contours are normalized to the source and the atmospheric concentrations, respectively. From Abreu (2005).....	12
Figure 2-6.	Normalized soil gas concentration distributions for oxygen and hydrocarbon undergoing aerobic biodegradation with a first-order rate $\lambda = 0.18 \text{ (h}^{-1}\text{)}$ and a vapor source concentration of 200 mg/L located beneath a slab-on-grade foundation at depths of 1 m, 3 m, 5 m and 8 m below ground surface. Hydrocarbon and oxygen contours are normalized to the source and the atmospheric concentrations, respectively. From Abreu (2005).....	13
Figure 4-1.	Considerations for vertical profiles at relatively flat sites (e.g., consistent distance between the ground surface and the vapor source depth) with consistent stratigraphy.	23
Figure 4-2.	Considerations for vertical profiles at sites with significant spatial variability in the distance between ground surface and the vapor source depth.....	24
Figure 4-3.	Sub-slab-to-indoor-air attenuation.	31
Figure 7-1.	Flowchart for data evaluation.	51

Tables

Table 4-1.	Considerations for Samples Collected Immediately above the Vapor Source	25
Table 4-2.	Considerations for Samples Collected Laterally Mid-Way between the Vapor Source and the Building Location	26
Table 4-3.	Considerations for Samples Collected Adjacent to the Base of an Existing Building Foundation or Basement.....	27
Table 4-4.	Considerations for Samples Collected Immediately below the Building Foundation or Basement	28
Table 4-5.	Considerations for Samples Collected within the Footprint of a Future Building Location	29
Table 6-1.	Common Analytical Methods	48
Table 7-1.	Example Comparisons of Biodegradation Stoichiometry and Fluxes.....	55

1.0 Introduction

Topic:

This section provides general information about the subsurface-vapor-to-indoor-air exposure pathway.

Purpose:

To define the following activities for collecting and interpreting soil gas samples:

- Collecting information
- Identifying sample locations
- Determining sample collection methods
- Selecting sample analytical methods
- Interpreting results.

Significance:

Soil gas data can be used to assess for significant concentrations of petroleum hydrocarbon vapors in the subsurface, to determine if vapor migration to a building is occurring, to estimate possible indoor air concentrations, and to identify significant attenuation of vapor transport by natural processes.

Soil gas sampling has been conducted for many years as a tool for evaluating the distribution of chemicals of concern in soil and groundwater, for guiding site characterizations, and for monitoring remedial action progress. However, soil gas data collected for a site characterization are generally focused on developing an understanding of the location and distribution of chemicals of concern in environmental media (e.g., soil, groundwater) and not on determining the definitive concentrations of chemicals of concern in soil gas. As a result, the methodologies used for traditional site characterizations may not be appropriate for evaluating the subsurface-vapor-to-indoor-air exposure pathway.

When assessing the subsurface-vapor-to-indoor-air pathway, an initial screen is conducted to identify those sites where further site-specific investigation and assessment are warranted. As the sampling of indoor air poses many practical and technical challenges, the ensuing site-specific pathway assessment often focuses on soil gas collection and analysis (as described in API 1998). For the evaluation of the subsurface-vapor-to-indoor-air exposure pathway, soil gas samples are collected to:

- Establish a snapshot of the concentrations of chemicals of concern in soil gas at a location along the exposure pathway between the source and the building location
- Analyze the potential for human receptors to be exposed in indoor environments
- Predict the expected indoor air concentration based on the soil gas concentrations using an estimated attenuation factor

- Account for the fate and transport processes between a sampling location and the indoor environment.

In the case of petroleum hydrocarbons, aerobic biodegradation has the potential to attenuate concentrations of chemicals of concern in soil gas and fluxes significantly as the vapors move toward buildings from soils or groundwater containing concentrations of petroleum hydrocarbon chemicals of concern. Therefore, soil gas data collected for the subsurface-vapor-to-indoor-air exposure pathway need to be focused on the purpose and use of the data and be based on these specific data-quality objectives.

The collection and use of soil gas data to evaluate the subsurface-vapor-to-indoor-air exposure pathway is a relatively new approach for this exposure pathway, and limited information is available on the appropriate methodologies. To address this need, options for the collection, analysis, and interpretation of soil gas data are presented in this document. This document emphasizes conceptual models for vapor transport in the formulation of sampling plans and data analysis and presents information needed to support the selection of sample locations and depths. The overall process of collection and analysis of soil gas samples is supported through important reminders and checklists at the end of each section. A systematic process is provided in the data analysis section to check the collected data for inconsistencies and for determination of situations requiring further study.

Specifically, five basic activities have been identified for the collection and interpretation of soil gas samples. These activities include the following:

1. Collecting information to understand the characteristics of the site (Section 3.0, Appendix A)
2. Identifying the location or locations for soil gas sample collection (Section 4.0, Appendix B)
3. Determining the method or methods for collecting soil gas samples (Section 5.0, Appendix C)
4. Selecting the method or methods to analyze soil gas samples (Section 6.0, Appendix D)
5. Evaluating and interpreting the results (Section 7.0, Appendix E).

To present a basic understanding of the processes affecting the subsurface-vapor-to-indoor-air exposure pathway and a foundation for decisions on soil gas sampling, the user is first provided with a discussion of soil gas transport (Section 2.0). This is followed by a discussion of the five activities identified for the collection and interpretation of soil gas samples.

2.0 Soil Gas Transport and Soil Gas Profiles at Petroleum Hydrocarbon Impacted Sites

Topic:

The conceptual model for soil gas migration and expectations for soil gas profiles at petroleum hydrocarbon sites are discussed here.

Purpose:

To show how chemicals volatilize from impacted soil or groundwater and migrate to regions of lower chemical concentration (e.g., the atmosphere, conduits, basements).

Significance:

The migration of hydrocarbon vapors throughout most of the subsurface is thought to be primarily the result of diffusive transport processes. Other processes, such as advective soil gas flow, oxygen migration, and aerobic biodegradation, also can significantly affect the soil gas migration to buildings.

Soil gas migration is typically conceptualized as shown Figure 2-1. Chemicals volatilize from impacted soil or groundwater and migrate to regions of lower chemical concentration (e.g., the atmosphere, conduits, basements). Although Figure 2-1 schematically depicts houses, vapor intrusion to commercial buildings and other structures also can be of concern. This guidance is broadly applicable to all building scenarios.

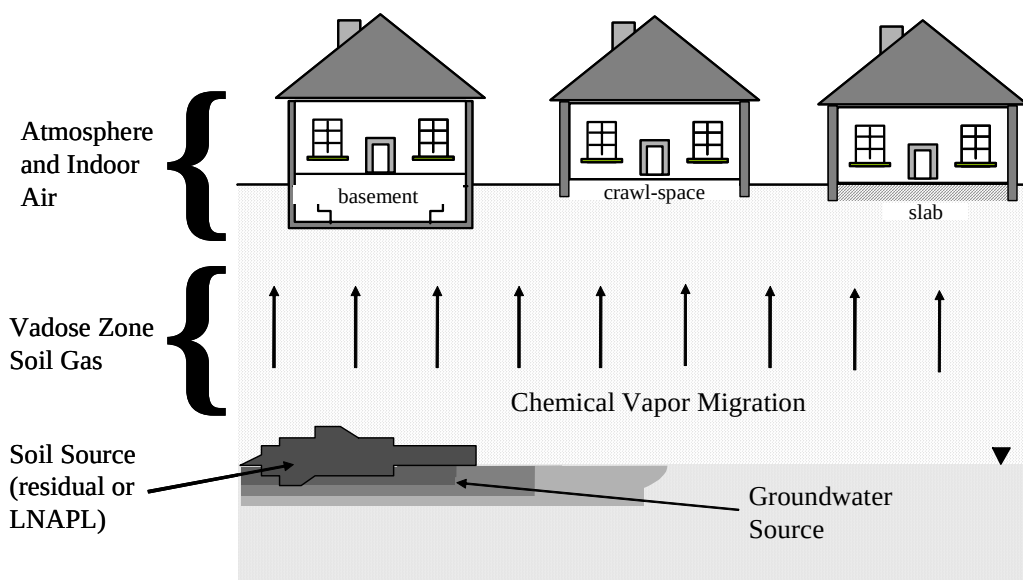


Figure 2-1. A typical conventional conceptual model of soil gas migration.

This migration of hydrocarbon vapors throughout most of the subsurface is thought to be primarily the result of diffusive transport processes. However, atmospheric pressure fluctuations also could contribute to vapor spreading, with the significance of the vapor spreading depending on the thickness and composition of the vadose zone. Near buildings or other enclosed spaces, significant advective soil gas flow fields may exist due to under- or over-

pressurization of a building (e.g., resulting from the operation of indoor appliances, such as a clothes dryer or the heating, ventilation, and air conditioning (HVAC) system; temperature differences; building-wind interactions).

Processes causing hydrocarbon vapor transport also can bring oxygen from the atmosphere to the subsurface. With petroleum hydrocarbon impacted soils, the soil gas composition and overall vapor migration also can be affected by aerobic and anaerobic biodegradation. For example:

- Oxygen moving down into the subsurface from the atmosphere and hydrocarbon vapors moving upward from the source will be consumed partially (or completely) in regions of active aerobic biodegradation, and carbon dioxide (CO₂) will be produced. This can result in the attenuation of hydrocarbon vapor fluxes (mass per total area per time) to the atmosphere and enclosed spaces. In some cases, this also can result in the creation of oxygen-depleted zones in the subsurface near and immediately above the source.
- Anaerobic decomposition of residual LNAPL in soils and dissolved chemicals of concern in groundwater may occur in the oxygen-depleted source zones, and methane (CH₄) may be generated. The methane gas then migrates upward in the direction of enclosed spaces and the atmosphere, and it can undergo aerobic biodegradation in the more oxygen-rich subsurface regions (as do the hydrocarbon vapors originating from the source as discussed above).

Thus, a more complex conceptual model is needed to adequately describe subsurface petroleum hydrocarbon vapor migration. One such conceptualization is shown in Figure 2-2.

Vapor Migration

Vapor migration results from the following processes:

Diffusion – the random kinetic energy of molecules results in a net movement of chemicals from areas of higher concentration to areas of lower concentration. The diffusive flux of chemicals is proportional to the concentration gradient (change in concentration divided by distance) and the effective porous medium diffusion coefficient (typical values are in the 0.001 - 0.01 cm²/s range for many chemicals and typical vadose zone conditions [see Figure 4 in Johnson 2002]).

Advection – the movement of chemicals with the bulk motion of the soil gas, where the flow of the bulk soil gas is the result of a soil gas pressure gradient caused by subsurface-building-pressure differences or atmospheric pressure fluctuations.

Diffusion is likely the dominant process far from a building and near the source, and advection is likely the dominant process near the building. The effect of atmospheric pressure fluctuations are not yet easily quantifiable, but it is likely that the resulting oscillatory movement of soil gas has a net effect on chemical migration that is small in shallow soils and of similar magnitude to diffusion in deeper soils (Massmann and Farrier 1992; Parker 2003).

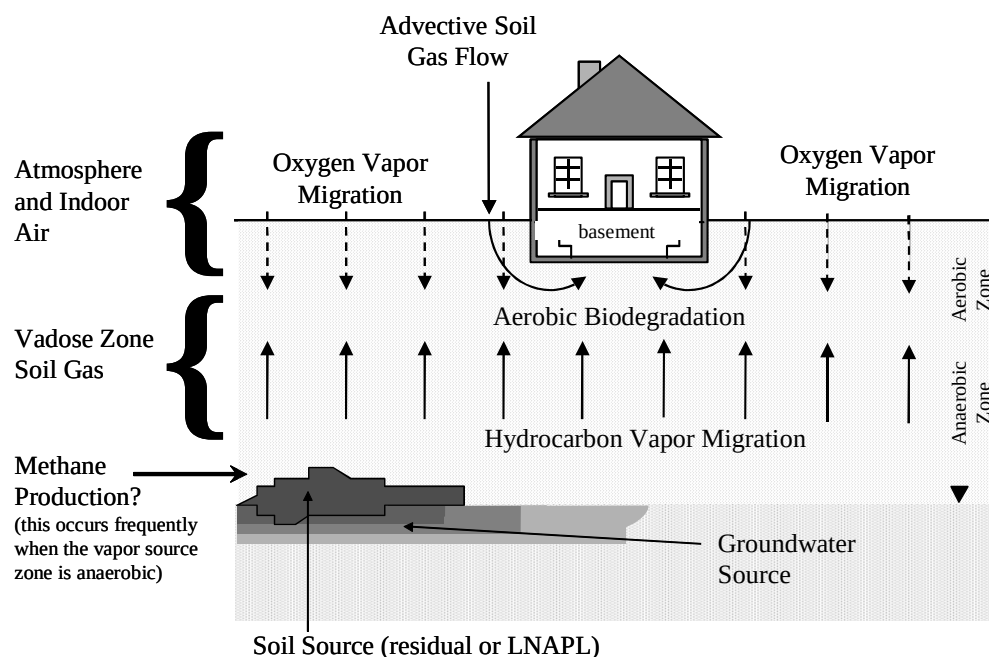


Figure 2-2. Revised conceptual model of soil gas migration at petroleum hydrocarbon impacted sites.

For further reading about soil gas migration processes as they relate to the vapor-to-indoor-air exposure pathway, see API 1998; Johnson 2002; Johnson et al. 1999; Little et al. 1992; and Roggemans et al. 2002.

2.1 Expectations for Soil Gas Profiles at Petroleum Hydrocarbon Impacted Sites

It is useful, when selecting appropriate soil-gas-sampling locations and depths, to be able to anticipate the qualitative nature of soil gas profiles. This information also is critical to assessing data quality after sampling and analyses are performed as discussed in Section 7.0. In this section, qualitative expectations for soil gas profiles are discussed, followed by the presentation of sample graphs of soil gas profiles in Section 2.2.

Based on the preceding discussion, the following observations are qualitatively expected at petroleum hydrocarbon impacted sites:

- The highest concentrations of chemicals of concern in soil gas will be found near the source.
- Concentrations of chemicals of concern in soil gas will decrease with distance away from the source zone absent advection and in the direction of the ground surface and enclosed spaces. Concentrations of chemicals of concern in soil gas also will decrease with distance laterally away from the source zone. However, it is possible for hydrocarbon vapors to become trapped below a layer of fine-grained soils or a moisture barrier. This would affect the concentration distribution.
- The composition of the hydrocarbon vapors at the source will reflect the composition of the petroleum liquid and the chemical properties of those components. Hydrocarbon

vapors at the source also may contain a significant fraction of methane if the soil gas in the vapor source zone is oxygen-depleted (anaerobic) and methanogenesis is occurring.

- Oxygen concentrations in the soil gas above impacted soils and groundwater will decrease with depth down through the soil, reaching zero directly above the source in most soils with shallow hydrocarbon impacts. Decreasing oxygen concentrations with depth also can be caused by background oxygen demand, especially in soils with high levels of natural organic matter. The contribution of background oxygen utilization can be assessed through soil gas monitoring in nearby un-impacted areas.

- In regions where oxygen concentrations decline with depth, increasing CO₂ concentrations with depth are generally observed through the aerobic region of the subsurface. CO₂ is produced during the aerobic biodegradation of petroleum hydrocarbons and the aerobic biodegradation of methane that might be produced under anaerobic conditions closer to some source zones. The decreases in oxygen with depth and the increases in CO₂ with depth should be consistent with each other as discussed later in Section 7.0.

- There will likely be some region of the subsurface in which aerobic biodegradation occurs. The significance of this process with respect to attenuation of concentrations of chemicals of concern in soil gas will depend primarily on:

- Surface conditions (to the extent that they limit oxygen migration into or hydrocarbon vapor migration out of the subsurface)
- Subsurface conditions (e.g., moisture content, lithology, nutrient availability)

Estimating the Time Necessary To Achieve Near-Steady-State Conditions

API (1998) and Johnson et al. (1999) discuss the importance of considering whether soil gas profiles have reached near-steady conditions, and they provide an equation for estimating the time necessary to achieve near-steady conditions, T_{ss} :

$$T_{ss} \approx \frac{R_v \theta_v L^2}{D_v^{eff}}$$

where D_v^{eff} is the effective diffusion coefficient discussed above (generally having values in the range 0.001 – 0.01 cm²/s), L is the distance from the source to ground surface (cm), θ_v is the vapor-filled void volume (often in the range 0.1 – 0.3 cm³-voids/cm³-soil), and R_v is the vapor-phase retardation factor (chemicals like the propanes, butanes, and pentanes, and oxygen will have R_v close to unity, while chemicals most often of concern because of health considerations [e.g., monoaromatic hydrocarbons, MTBE] will have vapor-phase retardation factors on the order of 10 < R_v < 100). Using these values, one can estimate times to reach near-steady conditions of a few hours to a few days for shallow sites (< 1 m depth to the vapor source); a few months to a few years for intermediate-depth sites (up to 3 m depth to the vapor source); and as much as a year to decades for deeper vapor sources (> 10 m depth). Aerobic biodegradation, if significant, will aid in reducing those times to reach near-steady conditions because the path length over which concentrations reduce significantly will be shorter.

- Concentrations of chemicals of concern and the total hydrocarbon concentration in soil gas at the source
- Thickness of the aerobic region
- Rate of biodegradation reactions.
- Because oxygen transport and aerobic biodegradation play a significant role when soil gas profiles are established, the soil gas profiles measured near buildings may be quite different from those that would be measured beneath them, especially if the building foundation reduces the oxygen flux to the subsurface. In those cases, the effects of aerobic biodegradation on the soil gas profile will be minimal beneath the foundation.

The discussion of soil gas profiles assumes that the releases that have generated the vapor source have been in place for some period of time and that the concentrations of chemicals of concern in soil gas have reached a near-steady condition. Some data indicate that soil gas profiles are affected by seasonal changes; therefore, the near-steady conditions still exhibit some temporal variability.

2.2 Measured Soil Gas Profiles at Petroleum Hydrocarbon Impacted Sites

To better illustrate the connection between the conceptual model shown in Figure 2-2 and measured vertical soil gas profiles, sample soil gas profiles are shown in Figure 2-3 and Figure 2-4. Each of these profiles is consistent with the conceptual model, yet each is qualitatively different from the others. In these plots, normalized soil gas concentrations (actual values divided by the maximum concentration at that site) are plotted as a function of depth below ground surface (z/L = actual depth to soil gas sample/depth to the source at that site).

Roggemans et al. (2002) performed an empirical assessment of soil gas profiles from petroleum hydrocarbon impacted sites and classified the data in terms of generalized hydrocarbon-oxygen soil gas profiles. Figure 2-3 represents specific examples of these profiles; all data originate from sites impacted by gasoline or other petroleum products. Note that most of the profiles presented by Roggemans et al. (2002) were measured near buildings or beneath paved surfaces; few were measured beneath buildings.

The profiles in Figure 2-3 and Figure 2-4 show oxygen utilization (as evidenced by decreasing concentrations with depth below ground surface) and some level of hydrocarbon concentration reduction, although it is variable.

In profile A of Figure 2-3, the oxygen penetrates about half of the distance down to the vapor source, but then is consumed by aerobic biodegradation over a short distance. This aerobic biodegradation is also reflected in the hydrocarbon concentration profile that shows the hydrocarbon concentration decreasing several orders of magnitude over a short distance near the anaerobic/anoxic transition zone. Profile A was the most frequently observed by Roggemans et al. (2002).

In profile B, the oxygen is present throughout the vadose zone, except at the vapor source zone interface. The corresponding hydrocarbon profile reflects reduction in hydrocarbon concentration by aerobic biodegradation with distance above the vapor source. The effect of aerobic

biodegradation, however, is less dramatic than in profile A. Profile B might be observed at shallow sites where transport distances are short and biodegradation is slow relative to the oxygen diffusion time scale through the vadose zone, or where vapor source concentrations are relatively low with respect to atmospheric oxygen concentrations (as might be the case above dissolved hydrocarbon groundwater plumes).

Profile C was collected beneath a basement overlying a high concentration vapor source. It is distinguished from the other profiles by the lack of oxygen at the monitoring points and less attenuation of the hydrocarbon vapor concentration. Relative to profile A, which also corresponds to a high concentration vapor source (but one beneath an uncovered surface) data suggest that in this case the building affects the oxygen transport and significance of the resulting aerobic biodegradation.

Profile D has an oxygen profile similar to that in profile B, but the hydrocarbon attenuation with distance away from the source is much more significant (i.e., a four-order-of-magnitude decrease in concentration over a very short depth). This profile occurs when the source is located in a zone having lower diffusion rates than the overlying soils; for example, this data set corresponds to a case where the vapors originate from within, or below, the capillary fringe.

Figure 2-4 presents vapor concentration profiles from a site impacted by heavier hydrocarbons (the source is composed of hydrocarbons in the C_{12} to C_{24} range). Of interest in Figure 2-4 is the production of methane gas from hydrocarbon decomposition and the subsequent attenuation of the methane gas within a short distance by aerobic biodegradation processes. Qualitatively, Figure 2-4 is similar to profile A in Figure 2-3, with the exception that methane is the dominant component of the hydrocarbon vapor concentration.

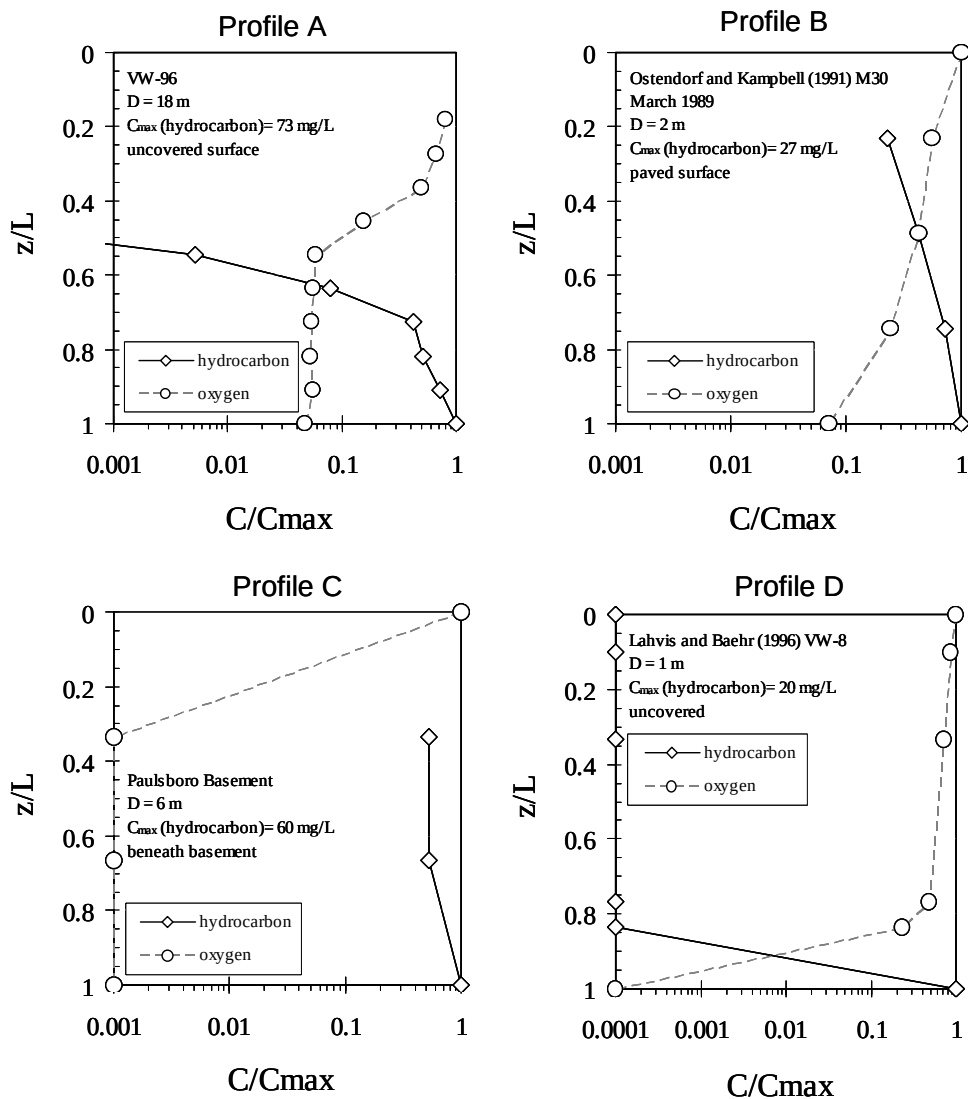


Figure 2-3. Soil gas profiles (Roggemans et al. 2002).

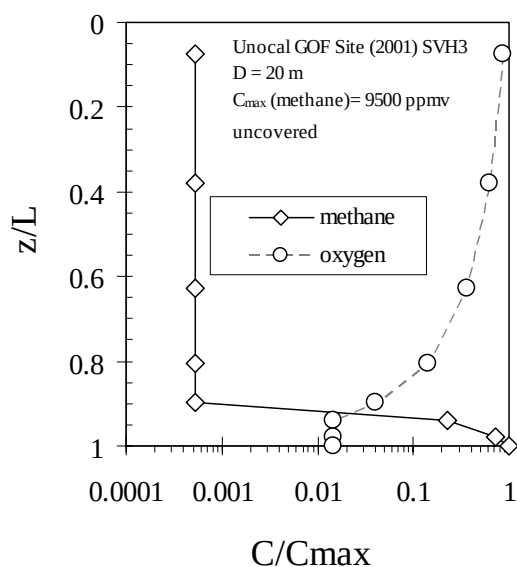


Figure 2-4. Soil gas profile at a site with methane production in the source zone (Johnson et al. 2003). This figure shows the soil gas profiles for oxygen (circles) and methane (diamonds).

Roggemans et al. (2002) attempted to correlate soil gas profiles with site characteristics and surface cover conditions, but were unable to find any obvious correlations (i.e., soil gas profiles below paved surfaces did not necessarily resemble those below buildings, and soil gas profiles beneath paved surfaces varied from site to site). Thus, the ability to anticipate the reduction in hydrocarbon vapor flux caused by biodegradation, based on site properties, is limited at this time. Soil-gas-profile data, therefore, are critical to understanding the subsurface processes and the net effect on hydrocarbon vapor migration to enclosed spaces.

To help visualize the impact that oxygen and aerobic biodegradation can have on vapor profiles at a site, **Figure 2-5** and **Figure 2-6** from Abreu (2005), show results from three-dimensional numerical simulations of vapor transport and aerobic biodegradation under homogeneous conditions near a building with a basement. **Figure 2-5** presents how significantly the chemical of concern and oxygen soil gas profiles and the attenuation factor can be affected by changes in the source concentration, for a progression of source concentrations from 20 mg/L to 200 mg/L. For reference, the Roggemans et al. (2002) report suggests that source vapor concentrations > 200 mg/L would be representative of gasoline source zones above the water table, while source soil vapor concentrations < 20 mg/L would be expected to occur near dissolved plumes down-gradient of source zones. In the 200 mg/L case, the effect of biodegradation is minimal relative to simulations without biodegradation, while the 2 mg/L source vapor concentration case corresponds to attenuation that is six orders of magnitude different from the 200 mg/L case ($\alpha = 5.6 \times 10^{-11}$ versus 7.1×10^{-5}). The major difference between the figures is the oxygen penetration depth beneath the building. In the 20 mg/L case, oxygen is found at elevated levels beneath the building footprint, so that chemical vapors are subjected to aerobic biodegradation along most of the transport pathway. It should be noted that these results are presented here simply to visualize trends and that they are specific to this depth; the influence of concentration

on attenuation factors for aerobically biodegradable chemicals is expected to be more significant as the source depth is increased (Abreu 2005).

Figure 2-6 illustrates the effect of depth on soil gas profiles and vapor attenuation coefficients for aerobically biodegradable chemicals. Simulations are shown for slab-on-grade foundations and relatively high (200 mg/L) soil vapor source concentrations at depths ranging from 1 m to 8 m below ground surface (Abreu 2005). The effect of biodegradation relative to non-biodegradation simulations is minimal for the shallower depths, but is very significant for the source located 8 m below ground surface.

Overall, the simulations illustrate that the significance of the effect of aerobic biodegradation is expected to be linked to the presence of oxygen beneath a foundation, and that attenuation due to aerobic biodegradation will increase with increasing source depth and decreasing source concentration.

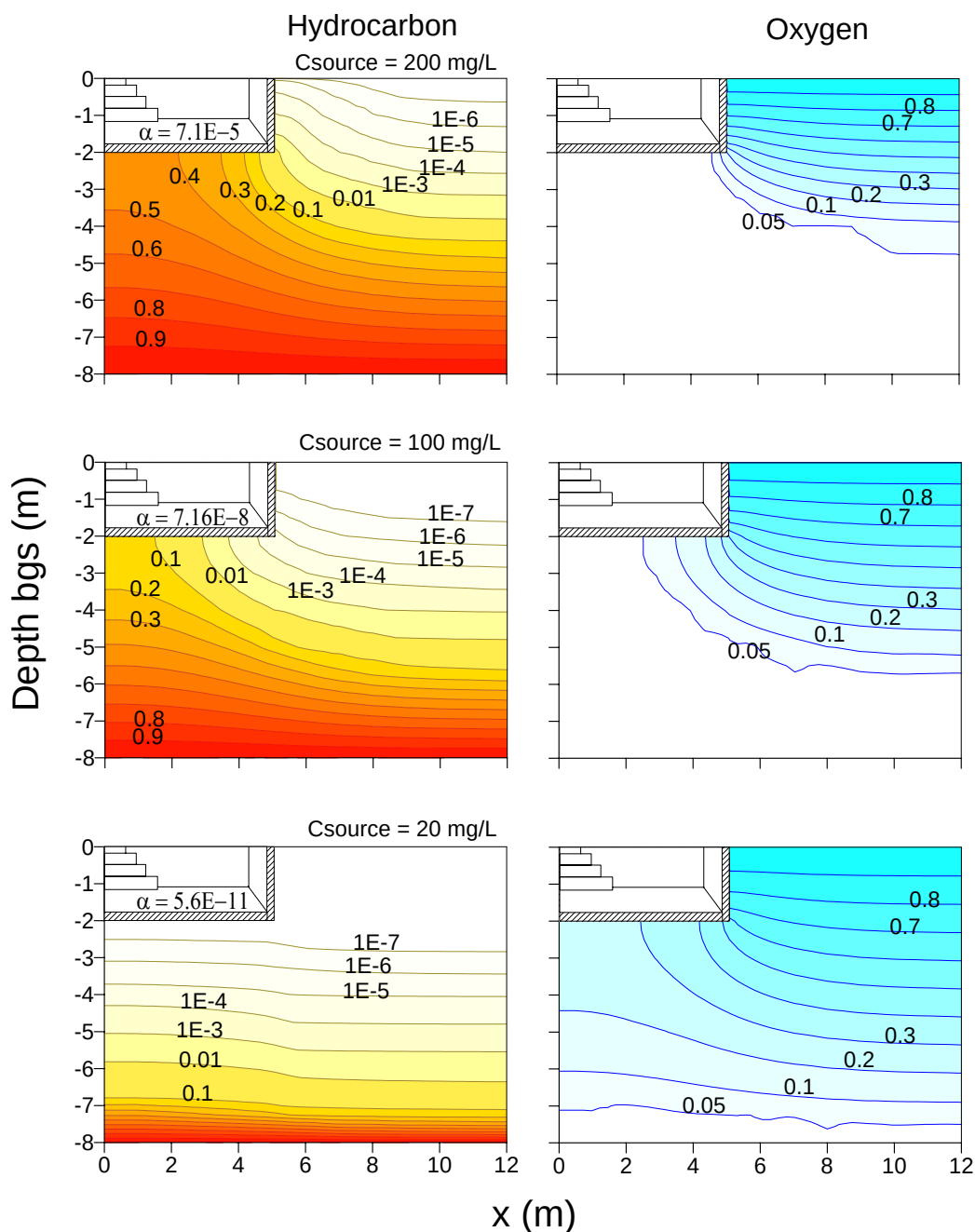


Figure 2-5. Normalized soil gas concentration distribution for oxygen and hydrocarbon undergoing aerobic biodegradation with first-order rate $\lambda = 0.18 \text{ (h}^{-1}\text{)}$ and vapor source at concentrations of 20 mg/L, 100 mg/L and 200 mg/L located underneath a basement foundation at a depth of 8 m below ground surface. Hydrocarbon and oxygen contours are normalized to the source and the atmospheric concentrations, respectively. (Abreu 2005).

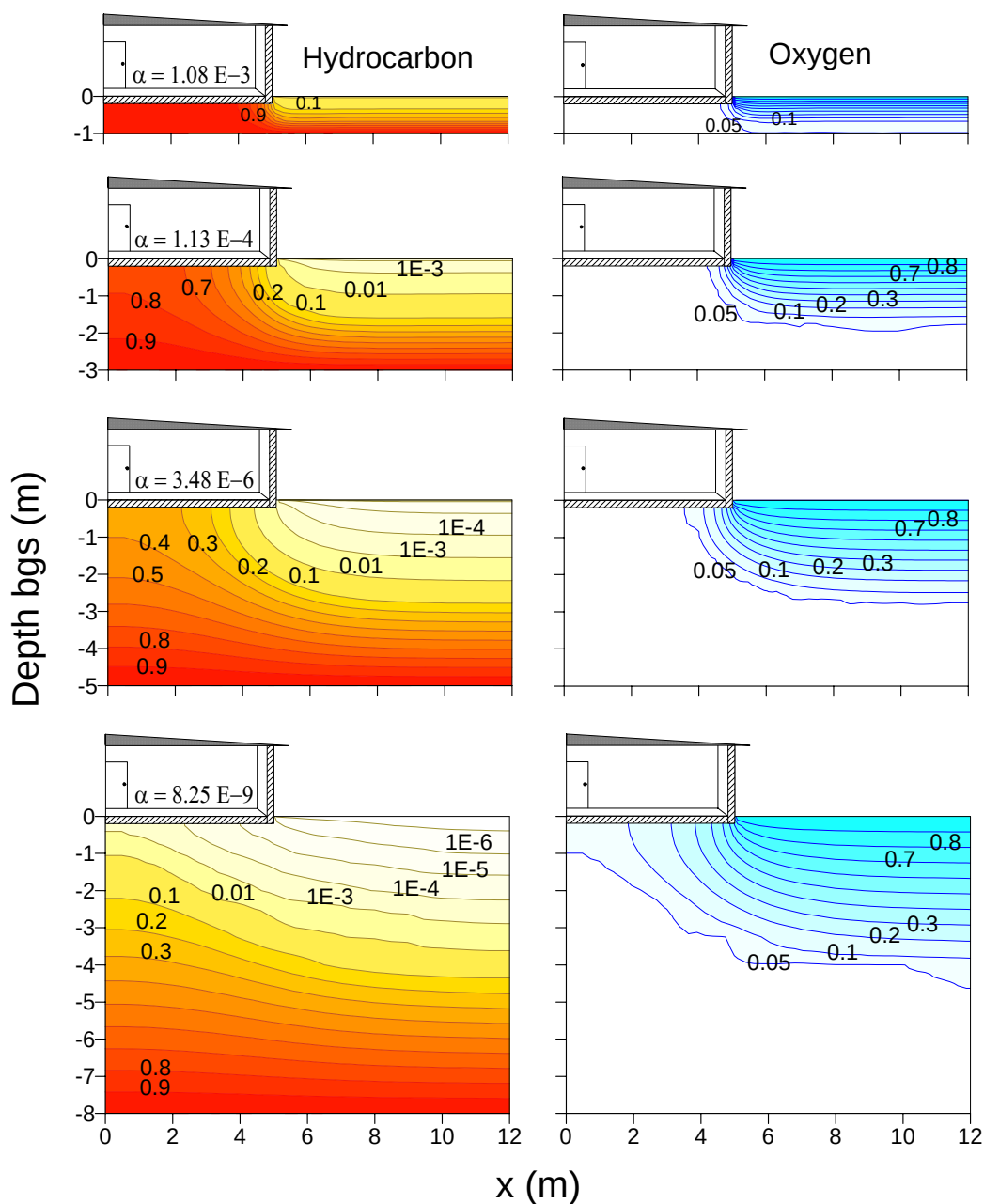


Figure 2-6. Normalized soil gas concentration distributions for oxygen and hydrocarbon undergoing aerobic biodegradation with a first-order rate $\lambda = 0.18 \text{ (h}^{-1}\text{)}$ and a vapor source concentration of 200 mg/L located beneath a slab-on-grade foundation at depths of 1 m, 3 m, 5 m and 8 m below ground surface. Hydrocarbon and oxygen contours are normalized to the source and the atmospheric concentrations, respectively. (Abreu 2005).

3.0 Conceptual Migration Model for Subsurface Vapor to Indoor Air

Topic:

This section provides background information to assist in developing a conceptual migration model for a specific site. The conceptual migration model is important for planning a soil-gas-sampling program.

Purpose:

To define a conceptual migration model for describing the vapor source characteristics, the current and future building locations and features, and the geologic profile of the subsurface. The model conveys a working hypothesis of the movement of vapor-phase chemicals of concern within the subsurface to a current or future building.

Significance:

The conceptual migration model should effectively communicate the important features of the site geology, hydrogeology, and petroleum hydrocarbon distribution and composition relevant to vapor migration. It is especially important that the site be reasonably well characterized for the purposes of planning soil gas sampling and laboratory analyses.

Prior to selecting sampling locations and depths, a site-specific conceptual migration model should be developed. The *conceptual migration model* describes the vapor source characteristics, including the vapor source location, size, environmental media, the concentrations of chemicals of concern and the potential for these to change with time. It also should include a description of the expected soil gas concentration distribution, and a discussion of:

- whether or not this distribution has reached near-steady conditions under current site conditions (e.g., present locations of buildings and surface cover),
- whether or not future site uses might alter the soil gas distribution (e.g., future building locations and surface features), and
- how the soil gas profile is expected to be influenced by geologic features.

The conceptual model should identify the current and reasonably potential future subsurface-vapor-to-indoor-air exposure pathways that may be present. The exposure

Vapor Transport along Utility Conduits

If vapor transport from the source area to the building could occur along utility conduits, then vapor sampling inside the utility conduits, manholes, or sumps should be considered in addition to vadose-zone-soil-gas sampling. Specific guidance for utility sampling is beyond the scope of this document; however, consideration should be given to field instrument screening at utility access points as an initial step to determine if the utility is acting as a conduit for vapors. It is important to establish in the conceptual migration model whether it appears that vapor migration is taking place along the utility backfill or if there is actual vapor transport inside the utility itself. Any utility sampling program must include safety precautions to protect personnel (e.g., oxygen and combustible gas monitoring, confined-space entry requirements) and to avoid damage to utilities.

pathways should be defined by the vapor source (e.g., soil, groundwater, light non-aqueous phase liquids [LNAPL]) and locations where the subsurface-vapor-to-indoor-air exposure pathway is of concern (e.g., current or potential future building). Specific buildings and future building sites should be identified. A description of the existing or anticipated building construction type (e.g., slab on grade, basement, multiple stories), design (e.g., basement or floor-slab thickness), and use (e.g., residential, commercial, industrial) should also be identified.

As part of the development of the conceptual migration model, it is important to review available information for the site to determine the state of knowledge about subsurface conditions and to identify specific information that is necessary to evaluate the subsurface-vapor-to-indoor-air exposure pathways. The conceptual migration model should effectively communicate the important features of the site geology, hydrogeology, and petroleum hydrocarbon distribution and composition relevant to vapor migration. It is especially important that the site be reasonably well characterized for the purposes of planning soil gas sampling and laboratory analyses, including information related to the:

- Types of petroleum hydrocarbons with volatile chemicals of concern (e.g., gasoline, jet fuel, diesel) that are currently or previously stored or handled at the site
- Petroleum hydrocarbon chemicals of concern and their concentrations in soil and groundwater (e.g., benzene, toluene, ethylbenzene, xylenes, MTBE, naphthalene). The particular chemicals of concern for a site, the use of the data, and the regulatory requirements are used to determine the appropriate laboratory analytical methods.
- Potential sources and source areas of vapors (e.g., soil, groundwater, LNAPL)
 - Presence of LNAPL, which may represent an expanding vapor source
 - Presence of residual LNAPL, which may represent a stable or reducing vapor source
 - For groundwater sources of vapors, it is useful to know whether the groundwater plume is expanding, stable, or shrinking as this will give an indication of the temporal variability of concentrations of chemicals of concern in soil gas and whether future concentrations in soil gas at a specific location are likely to be higher or lower than current concentrations. In addition, groundwater table fluctuations should be evaluated when assessing the temporal variability of groundwater sources.
- Geology and hydrogeology in the area of the site
 - Distinct soil strata and qualitative contrasts between them (e.g., finer- or coarser-grained soils, higher or lower moisture content strata). Finer-grained soils are generally more moist and tend to be the zones where there are significant concentration gradients. The coarser-grained soils often represent preferential vapor-migration zones.

- It is also important to consider whether there are relatively thin, finer-grained soil layers that may have a significant impact on vapor migration but can be difficult to detect during drilling.
- Approximate location of vapor sources in the subsurface and distances (lateral and vertical) between the vapor sources and the building location. The distances are important in determining the number of and locations for soil-gas-sampling probes.
- Possible preferential vapor-migration conduits (e.g., utility conduits, sewers)
 - Of particular interest are the utilities that intersect a vapor source and also connect to a building
 - If there is significant vapor migration in preferential pathways, then the measurement of concentrations of chemicals of concern in soil gas may not be representative of vapor concentrations that would migrate into an indoor environment. Other investigative techniques (e.g., utility vapor screening, indoor air measurements) for the subsurface-vapor-to-indoor-air exposure pathway may provide better data to evaluate the pathway. The user of this manual is directed to USEPA 2002a, and applicable state regulatory guidance for other methods to assess the vapor-to-indoor-air pathway (see PaDEP 2002; MaDEP 2002; WDHFS 2003; NJDEP 2004; CRWQCB 2003; CSDDEH 2003).
- Construction features of existing or future buildings (e.g., size, age, presence of foundation cracks, entry points for utilities).

Appendix A provides a summary of the information that is useful for understanding the site.

4.0 Development of a Strategy for Soil Gas Sampling

Topic:

This section deals with articulating the questions to be answered by the soil gas sampling and developing a strategy for soil gas sampling.

Purpose:

To develop a strategy for soil gas sampling based on:

- The practicality of collecting soil gas samples at a particular site
- A conceptual migration model for subsurface vapor to indoor air
- Questions to be answered by the sampling
- Regulatory requirements
- Technical issues.

Significance:

The development of a conceptual migration model, a discussion of the sampling options, a list of key considerations, and an exploration of reasonable sampling scenarios for petroleum hydrocarbon impacted sites are needed to establish an effective soil-gas-sampling program.

Section 3.0 discusses the development of the conceptual migration model for subsurface vapor to indoor air. This section discusses options for collecting soil gas samples. Because the strategy for soil gas sampling may vary from site to site, prescriptive guidance on sampling locations, depths, and frequencies is not provided. However, a discussion of the sampling options, a list of key considerations, and reasonable sampling scenarios for petroleum hydrocarbon impacted sites are discussed in this section. Local regulatory agencies may have sampling guidance that differs from that presented here. Appendix B provides worksheets for three typical scenarios that can be used for planning sampling locations.

The options for soil gas sample collection discussed in this section are based on consideration of:

- The practicality of collecting soil gas samples at a particular site
- A conceptual migration model for subsurface vapor to indoor air
- Questions to be answered by the sampling
- Regulatory requirements
- Technical issues.

Information about site considerations for sampling is included in Section 5.0 and in Appendix C.

In developing a soil-gas-sampling strategy, the questions to be answered by the soil gas sampling should be clearly articulated prior to designing the soil-gas-sampling plan. The questions to be answered by soil gas sampling at petroleum hydrocarbon impacted sites are often similar to one or more of the following:

1. Is the subsurface-vapor-to-indoor-air exposure pathway currently complete for individual chemicals of concern?

2. Are concentrations of chemicals of concern in soil gas currently above applicable regulatory action levels or other levels of concern?
3. Is biodegradation contributing to the attenuation of hydrocarbon vapors between the source and building at this site?
4. How might the answers to questions (1) to (3) change when considering plausible future activity and land-use scenarios?

The sampling approach selected for a site will depend on the site-specific conditions and the questions to be answered about the site. The selection of sampling locations and depths needs to consider the conceptual migration model (e.g., location of the vapor sources and the buildings of concern, the expected vapor distribution, and characteristics of the subsurface). It is likely that a phased program of soil gas sampling may be used at some sites, while at other sites the conditions may indicate that specific types of sampling and specific sampling locations are appropriate. The basic sampling approaches include:

- Point samples at specific depths in one or more lateral locations. These may be collected using temporary driven probes or by installing permanent soil-gas-sampling probes.
- Vertical profiles of samples at two or more depths. These can be installed at one or more lateral locations, called *transects*. These soil gas samples may be collected using temporary driven probes or by installing permanent soil-gas-sampling probes.

4.1 General Approach

Below are three basic steps in the selection of soil-gas-sampling locations.

1. Develop a conceptual migration model describing the current or potential future subsurface-vapor-to-indoor-air exposure pathways. The model may require modification as soil gas data are collected.
2. Identify the questions to be answered by the soil gas sampling and any regulatory requirements.
3. Select the sampling approach, the locations, and depths to provide information sufficient to assess the pathway and to answer the questions posed for the site.

Varied Sample Locations and Depths

It is a good idea to design the sampling program to collect soil gas samples at one or more locations or depths where concentrations are expected to be above the laboratory detection limits so that the field and laboratory methods can be verified. If all of the analytical results are below the laboratory detection limits, it is not easy to confirm that the field methods were implemented correctly (e.g., sample collection without dilution). In addition, there is increased confidence in the data when there are samples at two or more depths, given that the sample results are internally consistent and are consistent with the conceptual migration model.

4.2 Point Sampling

Point sampling is the collection of an individual soil gas sample from a specific depth at a single sample location. Often, soil gas sampling begins with point sampling. Consideration should be

given to how representative one sample will be of the concentrations of chemicals of concern in soil gas either spatially or temporally. It may be necessary to collect several point soil gas samples to develop an understanding of the distribution of concentrations of chemicals of concern in soil gas. A discussion of sampling frequency is given in Section 4.6.

Point sampling is often implemented when conducting an initial assessment of the subsurface-vapor-to-indoor-air exposure pathway. Point samples are collected at a specified depth, and the concentrations of chemicals of concern in soil gas are compared with chemical- and depth-specific target levels. The concentrations of chemicals of concern in soil gas also may be compared to measured concentrations of the chemicals of concern in ambient air samples. The most common locations for point sampling are immediately adjacent to, or beneath, a building foundation and at the vapor source. Use of the latter presumes that the location of the vapor source is known with confidence, and this may or may not be the case at a given site. If the concentration of a chemical of concern in soil gas is above the target level, then a more site-specific analysis should be conducted or remedial action should be implemented. Concentrations of chemicals of concern in soil gas below target levels indicate that the subsurface-vapor-to-indoor-air exposure pathway may not be significant. See Section 7.0 for more information about data analysis.

Another application of point sampling may be to evaluate the results of simple, conservative models of vapor transport in soil or from groundwater. Where modeling indicates that there may be concentrations of chemicals of concern above target levels at a building, it might be appropriate to collect several point soil gas samples to compare to the model results and further investigate if the pathway is actually complete.

Point samples may be collected using temporary driven probes or permanent probes as described in Section 5.1. It is important that the soil gas sample collected from a point sample is appropriate for the comparison. Therefore, the decision on the location and depth of the point sample should consider the vapor source (e.g., soil, groundwater, LNAPL), the mobility of the source (e.g., groundwater), and the impacts of heterogeneity in soil.

4.3 Transects and Vertical Profiles

Questions (1) and (2) at the beginning of this section arguably can be assessed with the collection of representative soil gas samples either at the vapor source or immediately adjacent to or beneath a foundation. In some situations, that information may be sufficient. In other circumstances, the added knowledge that comes from lateral transects and vertical profiles may be valuable for the following reasons:

- The assessment of the subsurface-vapor-to-indoor-air exposure pathway is typically triggered by the knowledge that a vapor source (e.g., petroleum hydrocarbon impacted soils or groundwater) is present in close proximity to a building (or future building location). If a single sample is collected near the building foundation and that sample results in non-detectable concentrations of chemicals of concern in soil gas, then there may be some question about the soil gas collection method or representativeness of that single soil gas sample. If a sample also were collected near the vapor source and this

sample were to have detectable concentrations of the expected magnitude, then the confidence in the validity of the near-foundation sample increases.

- The major difference between petroleum hydrocarbon impacted sites and sites impacted with other volatile chemicals of concern (e.g., chlorinated hydrocarbon impacted sites) is that aerobic biodegradation can be a significant contributor to the overall attenuation of petroleum hydrocarbon chemical of concern vapors as they migrate in soil from the source toward the building and ground surface. At some sites, very high total hydrocarbon vapor concentrations (e.g., within 10-percent of the lower explosive limits) will be detected near the source, and very low, or non-detectable, concentrations will be present near the buildings of concern. In this case, the collection of soil gas samples at points between the source and building, and review of the total hydrocarbon concentration, as well as chemical of concern concentration and oxygen-soil-gas profiles, will help to establish aerobic biodegradation as a key attenuation mechanism.
- Confidence in the overall understanding of vapor migration at a site is increased when consistency exists between the conceptual migration model and the soil gas profiles and transects.

Aerobic Biodegradation

Establishing the significance of aerobic biodegradation as it relates to hydrocarbon fluxes and indoor air concentrations requires a series of samples collected along the subsurface-vapor-migration pathway and analyzed for chemicals of concern and respiration gases. At many sites, the source is located directly beneath a building and vertical profiling is sufficient in those cases. At other sites where the source is displaced laterally from the building, a lateral series of vertical profiles between the source and building may be necessary.

This discussion has been included here to provide some insight to the underlying emphasis on vertical profiles and transects in this document. As stated above, point samples at key locations may be sufficient to determine whether the exposure pathway is complete or significant.

One of the unique features of petroleum hydrocarbon impacted sites is the potential for chemical of concern vapor fluxes and concentrations to be significantly attenuated by aerobic biodegradation. To establish the occurrence of aerobic biodegradation, a single sample might be sufficient—in particular, a sample showing depleted oxygen levels (and increased carbon dioxide); however, the estimation of attenuation rates resulting from aerobic biodegradation requires a soil gas profile or transect between the vapor source and the building.

Lateral Distance Threshold

Recently there has been discussion concerning the need for a threshold lateral distance criterion. For example, the USEPA (2002a) proposes that the pathway is not complete and sampling is not necessary if the distance between a known source and the building is greater than 100 feet. For reference, the USEPA criterion was based primarily on the authors' professional judgment and practical considerations. Based on theoretical considerations, it is known that this distance criterion should consider the depth to the vapor source, the vapor source strength, the indoor-air target levels, and local geology (Abreu and Johnson 2004; Lowell and Eklund 2004). Thus, the USEPA's 100-foot distance might, or might not, be protective at every site. For petroleum hydrocarbon impacted sites, the 100-foot distance is likely sufficient for most sites, provided that the vapor source edge is well defined, vertical migration of oxygen is not significantly impeded by surface or subsurface features, and conditions that could promote lateral migration are not present (e.g., landfill gas production, highly layered soils)

In addition, confidence in the conceptual migration model for a site and in quantifying the attenuation is increased when vertical profile or transect data are available. As discussed above, this confidence increases when there is consistency within the soil gas data set (e.g., concentrations decrease along the path between the source and building, decreasing oxygen concentrations with depth) and when there is consistency between the geologic profile developed under the conceptual migration model and the soil gas data (e.g., higher concentration gradients through finer-grained soils).

4.3.1 Selection of Lateral Positions for Soil Gas Transects

Soil gas transects can be used when the vapor source (e.g., soil, LNAPL, groundwater) is not located directly beneath the building or location of a future building. Soil gas transects consist of two or more sampling locations between the source and the building of concern. The purpose of collecting soil gas transects is to demonstrate and quantify the attenuation of concentrations of chemicals of concern in soil gas moving laterally from the source to the building.

A basic sampling program might involve three sampling locations. For example:

- One sampling location at the edge of the source zone closest to the building of concern
- One sampling location mid-way between the source and building
- One sampling location at the building.

While these three sampling locations are likely sufficient, based on the experience of the authors, users might consider additional intermediate points if the spacing between sampling probes is more than about 50 feet.

Transect samples may be collected using temporary driven probes or permanent probes as described in Section 5.1. The location and depth of the transect samples should consider the vapor source (e.g., soil, LNAPL groundwater), the mobility of the source medium (e.g., groundwater), and the impacts of heterogeneity in soil.

4.3.2 Vertical Profiles

A soil-gas vertical profile consists of two or more samples collected from a single location between the top of the source and the ground surface or building foundation. The purpose of collecting soil-gas vertical profiles is to demonstrate and quantify the attenuation of concentrations of chemicals of concern in soil gas vertically from the top of the source to the ground surface or building foundation. For sites where the vapor source is directly beneath the building, soil-gas vertical profiles are typically used to determine the potential for and magnitude of vapor migration into the building. The following should be considered in selecting vertical sampling depths:

- To estimate the maximum concentration of chemicals of concern in soil gas, a sample is needed immediately above the vapor source
- To estimate the concentration of chemicals of concern in soil gas near the foundation, samples should be collected immediately adjacent to, or beneath, the building foundation
- To establish the occurrence and significance of aerobic biodegradation, two or more soil gas samples should be collected between the vapor source and the building foundation
- The vertical distance between adjacent samples based on practical considerations is usually not less than about 2 feet, and at some sites, this practical constraint might limit the number of samples collected
- For deeper sources, where the distance between the source and the building foundation is greater than approximately 40 feet, profiles consisting of five or more sampling depths are often necessary to provide resolution of the soil gas profile
- Sampling locations also may be selected based on the lithology of the site (e.g., in more permeable soil zones, whether natural or artificial, or at locations where changes in concentration are expected)
- When assessing sites where impacted groundwater, LNAPL, or a smear zone is the vapor source, a closer spacing of samples should be considered, relative to the remainder of the profile (e.g., several samples spaced 2 feet apart) near the groundwater table/capillary fringe, as the concentration gradients are often greatest at that depth.

A vertical profile could be developed using only three sample depths. However, depending on site-specific circumstances (e.g., depth to top of source area, lithology) four or more sample depths may be appropriate. Some situations preclude the use of vertically-nested soil gas probes or vertical profiling. As a rule of thumb, when groundwater is within a few feet of a foundation, it is likely that only one soil-gas-sampling depth is practical. The site characteristics and physical constraints will factor into the number of vertical samples.

Vertical profile samples may be collected using temporary driven probes or permanent probes as described in Section 5.1. The decision on the number of vertical profile samples should consider the vapor source (e.g., soil, groundwater, LNAPL), the depth of the source (e.g., groundwater, LNAPL), and the impacts of heterogeneity in soil. The lithologic profile, surface topography, and