January 2026

VAPOR INTRUSION TOOLKIT

VAPOR INTRUSION TECHNICAL AND REGULATORY GUIDANCE



Prepared By
The Interstate Technology & Regulatory Council (ITRC)
Vapor Intrusion Update Team

EXECUTIVE SUMMARY

The Interstate Technology & Regulatory Council's (ITRC) first guidance document on vapor intrusion (VI) was released in 2007, the *Vapor Intrusion Pathway: A Practical Guidance* (VI-1) and has served as the foundation for regulatory guidance across the country since its release. In 2014, ITRC released a follow-up vapor intrusion guidance document, *Petroleum Vapor Intrusion: Fundamentals of Screening, Investigation, and Management* (PVI-1), that focused on petroleum vapor intrusion and addressed several VI best practices that had been updated since 2007. In 2021, ITRC released the *Technical Resources for Vapor Intrusion Mitigation* (VIM-1), which provided fact sheets, technology information sheets, and checklists to summarize the latest science, practices, and new approaches to VIM in addition to the development and delivery of internet-based training modules, which have been attended by more than 7,000 attendees from across the world.

The ITRC Vapor Intrusion Toolkit (VI Toolkit) will replace, combine, and update all three previous ITRC VI guidance documents (2007 VI-1, 2014 PVI-1, and 2021 VIM-1) and provide a scientifically based, consensus approach to explain concepts and best practices regarding VI. The VI Toolkit includes:

- Vapor Intrusion Technical and Regulatory Guidance
- Fact Sheets
- Technology Information Sheets
- Checklists

The VI Toolkit represents the combined effort of more than 500 professionals from state and federal regulatory agencies, consultants, industry, and stakeholders from 2007 to 2025.

Due to variations in policy among regulatory agencies, the VI Toolkit is not intended to provide a single prescriptive approach for assessing the VI pathway. Instead, the VI Toolkit's purpose is to provide a generalized framework for evaluating the VI pathway and a description of the various tools available for screening, investigation, data evaluation, and mitigation. The VI Toolkit is intended to be used in conjunction with any applicable regulatory agency VI policy or guidance, as appropriate.

ABOUT ITRC

ITRC is a national coalition focused on developing tools and strategies to reduce interstate barriers to the deployment of innovative environmental technologies. ITRC produces documents and training to improve technical knowledge and expedite quality regulatory decision making while protecting human health and the environment. With private and public sector members from all 50 states and the District of Columbia, ITRC truly provides a national perspective. More information on ITRC is available at **https://www.itrcweb.org**.

ITRC is a program of the Environmental Research Institute of the States (ERIS), a 501(c)(3) organization incorporated in the District of Columbia and affiliated with the Environmental Council of the States (ECOS). ECOS is the national, nonprofit, nonpartisan association representing the state and territorial environmental commissioners.

DISCLAIMER

This material was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily

constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof and no official endorsement should be inferred.

The information provided in documents, training curricula, and other print or electronic materials created by the Interstate Technology & Regulatory Council ("ITRC" and such materials are referred to as "ITRC Materials") is intended as a general reference to help regulators and others develop a consistent approach to their evaluation, regulatory approval, and deployment of environmental technologies. The information in ITRC Materials was formulated to be reliable and accurate. However, the information is provided "as is" and use of this information is at the users' own risk.

ITRC Materials do not necessarily address all applicable health and safety risks and precautions with respect to particular materials, conditions, or procedures in specific applications of any technology. Consequently, ITRC recommends consulting applicable standards, laws, regulations, suppliers of materials, and material safety data sheets for information concerning safety and health risks and precautions and compliance with then-applicable laws and regulations. ITRC, ERIS and ECOS shall not be liable in the event of any conflict between information in ITRC Materials and such laws, regulations, and/or other ordinances. The content in ITRC Materials may be revised or withdrawn at any time without prior notice.

ITRC, ERIS, and ECOS make no representations or warranties, express or implied, with respect to information in ITRC Materials and specifically disclaim all warranties to the fullest extent permitted by law (including, but not limited to, merchantability or fitness for a particular purpose). ITRC, ERIS, and ECOS will not accept liability for damages of any kind that result from acting upon or using this information.

ITRC, ERIS, and ECOS do not endorse or recommend the use of specific technology or technology provider through ITRC Materials. Reference to technologies, products, or services offered by other parties does not constitute a guarantee by ITRC, ERIS, and ECOS of the quality or value of those technologies, products, or services. Information in ITRC Materials is for general reference only; it should not be construed as definitive guidance for any specific site and is not a substitute for consultation with qualified professional advisors.

Vapor Intrusion

Technical and Regulatory Guidance

January 2026

This document is a static PDF and is provided for informational purposes only. The content within is accurate as of the date of publication and will not be updated or maintained. Any references, links, or data contained herein may become outdated over time. For the most current information, please refer to the appropriate sources or contact the Interstate Technology & Regulatory Council. The Interstate Technology & Regulatory Council assumes no responsibility for any consequences resulting from the use of outdated or incorrect information.

Permission is granted to refer to or quote from this publication with the customary acknowledgment of the source. The suggested citation for this document is as follows:

ITRC (Interstate Technology & Regulatory Council). January 2026. Vapor Intrusion Toolkit. Washington, D.C.: Interstate Technology & Regulatory Council, Vapor Intrusion Update Team. **https://itrcweb.org/vapor-intrusion-toolkit/**.

TABLE OF CONTENTS

CHAPTER 1: INTRODUCTION 1

1.1. What Is the Purpose and Scope of This Document? 1

1.2. Who Should Use This Document? 2

1.3. Who Developed This Document? 2

1.4. Why Is This Document Important? 2

1.5. What Is the Vapor Intrusion Strategy? 2

1.6. Overview of Vapor Intrusion Technical and Regulatory Guidance Chapters 4

1.6.1. Vapor Intrusion 101 (Chapter 2) 4

1.6.2. Community Engagement (Chapter 3) 4

1.6.3. Conceptual Site Models (Chapter 4) 4

1.6.4. Site Screening (Chapter 5) 4

1.6.5. Iterative Investigation Process (Chapter 6) 5

1.6.6. Sampling and Analysis (Chapter 7) 5

1.6.7. Data Evaluation and Vapor Intrusion Risk Assessment (Chapter 8) 5

1.6.8. Modeling (Chapter 9) 5

1.6.9. Vapor Intrusion Mitigation (Chapter 10) 5

1.6.10. Vapor Intrusion Component Determination, Exit Points, and Closure (Chapter 11) 6

1.6.11. References, Glossary, and Acronyms 6

1.6.12. Acknowledgments 6

1.7. State Practices Survey 6

CHAPTER 2: VAPOR INTRUSION 101 7

2.1. What Is Vapor Intrusion? 7

2.1.1. Definition of Vapor Intrusion 7

2.1.2. Evolution of Vapor Intrusion Science and Regulatory Guidance 8

2.1.3. Vapor Transport 10

2.2. Important Vapor Intrusion Considerations 14

2.2.1. Regulatory Considerations 14

2.2.2. Community Engagement 14

2.2.3. Emergency and Rapid Response Situations 15

2.2.4. Background Sources of Chemicals 15

2.2.5. Spatial and Temporal Variability 16

2.2.6. How Is Petroleum Vapor Intrusion Different from Nonpetroleum Vapor Intrusion? 17

2.2.7. Subsurface Considerations 20

2.2.8. Clean Water Lenses 22

2.2.9. Emerging Vapor-Forming Chemicals 23

2.3. Vapor Intrusion Pathway Assessment Process 24

2.3.1. Preliminary Exposure Assessment, Vapor Intrusion Assessment, and Evaluation 25
2.3.2. Multiple Lines of Evidence 28
2.3.3. Use of Mathematical Models 29
2.4. Vapor Intrusion Mitigation 29
2.4.1. Emergency and Rapid Response 30
2.4.2. Active Mitigation Technologies 30
2.4.3. Passive Mitigation Technologies 30
2.4.4. Remediation and Institutional Controls 31
2.4.5. Vapor Intrusion Assessment Exit Points and Closure 31

CHAPTER 3: COMMUNITY ENGAGEMENT 32
3.1. Introduction 32
3.2. Community Engagement Plan and Approaching Stakeholders for Investigation 33
3.2.1. Identify Stakeholders 33
3.2.2. Role of Risk Perception 34
3.2.3. Consistent Messaging 34
3.2.4. Community Engagement Tools 35
3.2.5. Property and Building Access 36
3.2.6. Nonresidential Buildings 37
3.2.7. Public Repositories 37
3.3. Stakeholders' Concerns 38
3.3.1. Health 38
3.3.2. Other Initial Concerns 38
3.3.3. Investigation and Mitigation Concerns 40
3.4. Explanation of Complex Topics 42
3.4.1. What Is Vapor Intrusion? 42
3.4.2. Explaining Risk Assessment 43
3.4.3. Building Type Affects Pathway 44
3.4.4. Sources 45
3.4.5. Contaminants 46
3.4.6. Sampling–Types and Uses of Samples 47
3.5. Mitigation (Remedy Needed) 49
3.5.1. Everyone Is a Risk Communicator 49
3.5.2. Mitigation Is Not the Same as Remediation 49
3.5.3. Explaining Mitigation Systems 49
3.5.4. May Involve Cleaning Basements 50
3.6. Long-Term Stewardship Best Practices 50
3.7. Development 51
3.7.1. Local Government 51
3.7.2. Construction Workers 52
3.7.3. Future Building Occupants 52

3.7.4. Site Neighbors 52
3.7.5. Long-Term Management 53

CHAPTER 4: CONCEPTUAL SITE MODEL 54

4.1. Introduction 54
4.2. Components of a Conceptual Site Model 55
4.2.1. Site History 55
4.2.2. Historical, Current, and Future Site Use 57
4.2.3. Background Sources 57
4.2.4. Receptor and Risk Scenario 58
4.2.5. Sources of Vapor 58
4.2.6. Nature and Extent of Contamination 59
4.2.7. Soil 59
4.2.8. Groundwater 60
4.2.9. Nonaqueous-Phase Liquids 60
4.2.10. Soil Vapor 62
4.2.11. Indoor Air 63
4.2.12. Degradation of Vapor 63
4.2.13. Geology and Hydrogeology 63
4.2.14. Climate and Weather 63
4.2.15. Building Characteristics 64
4.2.16. Preferential Pathways 64
4.3. Refining the Conceptual Site Model 67

CHAPTER 5: SITE SCREENING 69

5.1. Introduction 69
5.1.1. Screening Requirements 71
5.1.2. Conservatism in Vapor Intrusion Screening 71
5.2. Step 1–Preliminary Vapor Intrusion Exposure Assessment and Screening Data Evaluation 71
5.2.1. Preliminary Vapor Intrusion Exposure Assessment 71
5.2.2. Screening Data Evaluation 71
5.2.3. Evaluation of Emergency or Rapid Response 72
5.2.4. Community Engagement 73
5.3. Step 2–Initial Vapor Intrusion Screening 73
5.3.1. Precluding Factors Assessment 73
5.3.2. Distance-Based Screening 74
5.4. Step 3–Refined Vapor Intrusion Screening 77
5.4.1. Concentration-Based Screening 77
5.4.2. Mass-Flux-Based Screening 81
5.5. Vapor Intrusion Screening Outcomes 85

CHAPTER 6: ITERATIVE INVESTIGATION PROCESS 86
6.1. Step 1–Choose Investigative Approach 87
6.2. Step 2–Design the Investigation Work Plan 89
6.2.1. Conceptual Site Model 89
6.2.2. Data Gaps 89
6.2.3. Determining Sample Locations 90
6.2.4. Background Sources 92
6.2.5. Sampling and Analysis Plan 92
6.2.6. Community Outreach and Information Plan 93
6.2.7. Scheduling Investigation 93
6.3. Step 3–Implement Work Plan 93
6.3.1. Complete Pre-Field Activities 93
6.3.2. Complete Field Activities 95
6.4. Step 4–Site-Specific Evaluation 95

CHAPTER 7: SAMPLING AND ANALYSIS 96
7.1. Introduction and Overview 96
7.2. Real-Time Data Collection 99
7.2.1. Handheld Logging Instruments 101
7.2.2. Real-Time Chemical-Specific Analyzer 103
7.2.3. Mobile Laboratories 104
7.3. Methodologies for Installing Media Sampling Points 105
7.3.1. Indoor and Outdoor Air Sampling Points 105
7.3.2. Crawl-Space Sampling Points 107
7.3.3. Active Sub-Slab Vapor Probe Installation 108
7.3.4. Active Soil Vapor Probe Installation 111
7.3.5. Passive Soil Vapor Probes 116
7.4. Sampling Methods 116
7.4.1. Active Sampling Methods 116
7.4.2. Passive Sampling Methods (TO-17 and 8260D) 134
7.4.3. Soil Vapor Sampling from Existing Groundwater Wells 136
7.4.4. Quality Control Samples 137
7.4.5. High-Volume Soil Vapor Sampling 138
7.5. Sampling Locations and Frequency 138
7.5.1. Indoor Air 138
7.5.2. Crawl Space / Cellar 140
7.5.3. Outdoor Air 140
7.5.4. Soil Vapor and Sub-Slab Vapor 141
7.6. Other Media Sampling Methods 147
7.6.1. Groundwater 147
7.6.2. Soil 148

7.6.3. Nonaqueous-Phase Liquid 151
7.6.4. Sewer and Other Utility Conduits 153
7.7. Supplemental Tools and Methodologies for Physical Vapor Intrusion Characteristics 156
7.7.1. Additional Uses for High-Volume Sampling 156
7.7.2. Differential Pressure Monitoring and Building Pressure Control 156
7.7.3. Flux Chamber and Other Flux Measurement Devices 156
7.7.4. Using Tracers for the Determination of Slab-Specific Attenuation Factors and Room Ventilation Rates 157
7.7.5. Vapor-Forming Chemical Source Determination 158
7.8. Advantages and Disadvantages of Various Investigation Strategies 158
7.8.1. Relative Advantages of Investigation Methods 158
7.8.2. Common Vapor Intrusion Investigation Limitations 158
7.9. Per- and Polyfluoroalkyl Substances Considerations 164
7.9.1. Considerations When Sampling for Per- and Polyfluoroalkyl Substances 164
7.10. Analytical Methods 164
7.10.1. Choosing an Appropriate Analytical Method 164

CHAPTER 8: DATA EVALUATION AND VAPOR INTRUSION RISK ASSESSMENT 168
8.1. Introduction 168
8.2. Data Evaluation 168
8.2.1. Data Quality Review 169
8.2.2. Key Data Evaluation Steps 170
8.2.3. Outcomes of the Data Evaluation Process 175
8.3. Generic or Default Screening Levels 175
8.4. Screening Risk Assessment 176
8.4.1. Exposure 177
8.4.2. Inputs and Methods 177
8.4.3. Results 179
8.4.4. Interpretation and Multiple Lines of Evidence 179
8.5. Site-Specific Screening Levels 180
8.5.1. Alternative Receptors and Exposure Parameters 180
8.5.2. Background Concentrations 181
8.5.3. Attenuation Factors 182
8.5.4. Modeling 184
8.5.5. Special Scenarios 185
8.6. Site-Specific Risk Assessment 185
8.6.1. Hazard Identification 186
8.6.2. Toxicity Assessment 189
8.6.3. Risk Characterization 190
8.6.4. Uncertainty Analysis 190
8.6.5. Interpretation and Multiple Lines of Evidence 191

8.7. Cleanup Levels 191

CHAPTER 9: MODELING 193

9.1. Purpose and Limitations 193

9.2. Use of Models for Assessing Vapor Intrusion 194

9.2.1. Define Modeling Objectives 194

9.2.2. Review Conceptual Site Model 197

9.2.3. Select an Appropriate Model 197

9.2.4. Determine Model Inputs 199

9.2.5. Conduct Model Sensitivity Analysis 199

9.2.6. Verify Model Output and Interpret Results 200

9.2.7. Present Model Predictions to Stakeholders and Regulatory Authorities 200

9.3. Review of Vapor Intrusion Models 201

9.3.1. Vapor Intrusion Screening Levels Calculator 202

9.3.2. Johnson and Ettinger Model 202

9.3.3. BioVapor Model 203

9.3.4. PVIScreen Model 204

9.3.5. Lateral Vapor Migration Models 204

CHAPTER 10: VAPOR INTRUSION MITIGATION 206

10.1. Rapid Response 208

10.1.1. Occupant, Community, and Stakeholder Considerations 209

10.2. Remediation and Institutional Controls 209

10.2.1. Remediation as Vapor Intrusion Mitigation 209

10.2.2. Institutional Controls as Vapor Intrusion Mitigation 210

10.2.3. Other Considerations 210

10.2.4. Occupant, Community, and Stakeholder Considerations 211

10.3. Active Vapor Intrusion Mitigation Systems 211

10.3.1. Common Active Mitigation Strategies 212

10.3.2. Considerations for Design and Implementation 212

10.3.3. Post-Installation Performance Verification 212

10.3.4. Vapor Intrusion Mitigation Systems Operation, Maintenance, and Monitoring 213

10.3.5. Occupant, Community, and Stakeholder Considerations 213

10.4. Passive Vapor Intrusion Mitigation Systems 213

10.4.1. Considerations for Design and Implementation 214

10.4.2. Occupant, Community, and Stakeholder Considerations 214

10.5. Considerations for Design and Implementation of Vapor Intrusion Mitigation Approaches 214

10.5.1. Design and Implementation Considerations 214

10.5.2. Construction Quality Assurance 215

10.5.3. Post-Installation Verification 215

10.5.4. Operation, Maintenance, and Monitoring 215

10.6. Vapor Intrusion Mitigation Curtailment and Closure Strategies 216

CHAPTER 11: VAPOR INTRUSION COMPONENT DETERMINATION, EXIT POINTS, AND CLOSURE 217

11.1. Overview 217

11.2. Community Engagement Considerations 218

11.3. No Vapor Intrusion Component Determination 221

11.4. Site Screening and Data Evaluation 221

11.4.1. Data Evaluation and Vapor Intrusion Risk Assessment 222

11.4.2. Vapor Intrusion Mitigation 223

11.5. Managed Vapor Intrusion Closure 224

11.6. Vapor Intrusion Closure 226

ACKNOWLEDGMENTS 228

GLOSSARY 242

ACRONYMS 252

REFERENCES 261

APPENDIX A: SUMMARY OF STATE VAPOR INTRUSION PRACTICES A-1

APPENDIX B: EXAMPLE DOCUMENTS B-1

APPENDIX C: CHEMISTRY OF PETROLEUM C-1

APPENDIX D: COMMON TYPES OF PETROLEUM SITES D-1

APPENDIX E: APPLICATION OF PRECLUDING FACTORS E-1

APPENDIX F: DISTANCE-BASED SCREENING AT PETROLEUM VI SITES F-1

APPENDIX G: OVERVIEW OF VAPOR INTRUSION MODELS G-1

APPENDIX H: BIODEGRADATION MODEL (BIOVAPOR) PROCESSES, INPUTS, AND CASE EXAMPLES H-1

APPENDIX I: JOHNSON AND ETTINGER MODEL INPUTS, OUTPUTS, AND CASE EXAMPLES I-1

APPENDIX J: VAPOR INTRUSION MITIGATION SYSTEM CONSTRUCTION QUALITY ASSURANCE PLAN OUTLINE J-1

APPENDIX K: VAPOR INTRUSION MITIGATION STEWARDSHIP PLAN OUTLINE K-1

APPENDIX L: VAPOR INTRUSION MITIGATION EXAMPLE CURTAILMENT PLAN OUTLINE L-1

LIST OF FIGURES

Figure 1-1. Vapor intrusion strategy flowchart. 3
Figure 2-1. Conceptualized vapor intrusion pathway. 7
Figure 2-2. Sources of vapor-forming chemicals. 10
Figure 2-3. Diffusive transport. 11
Figure 2-4. Advective transport. 12
Figure 2-5. Dilution of soil vapor in indoor air. 13
Figure 2-6. Biodegradation. 17
Figure 2-7. Lateral screening and vertical separation distances. 21
Figure 2-8. Clean water lens. 23
Figure 2-9. Vapor intrusion pathway assessment process. 24
Figure 2-10. General conceptual site models for the vapor intrusion pathway. 26
Figure 4-1. Example conceptual site model components displayed graphically. 56
Figure 4-2. A generalized representation of the elements of a light nonaqueous-phase liquid release and associated migration pathways. 61
Figure 4-3. Potential barriers to vapor intrusion: (A) no barriers, (B) impermeable building foundation, (C) positive building differential pressure, (D) saturated clay/silt layer between vapor source and building, (E) biodegradation of vapors in the vadose zone, and (F) clean water lens at the top of the water table. 65
Figure 5-1. Generalization of vapor intrusion screening process. 70
Figure 5-2. Decision tree associated with implementation of distance-based screening criteria. 75
Figure 5-3. Conceptualization of various mass-flux-based screening methods involving (A) analyses of depth-discrete concentrations ($C_{SG\ (z1-z3)}$) of vapor-forming chemicals (VFCs) in soil vapor using vapor transport modeling and a default or building-specific estimate of the effective diffusion coefficient of vadose-zone soil (D_{eff}), (B) measurements of VFC concentrations in indoor air (C_{IA}) and airflow rates across a blower door associated with indoor air depressurization (e.g., building pressure cycling - Q_{BPC}), or (C) measurements of VFC concentrations and airflow rates associated with sub-slab soil vapor depressurization (Q_{SSG}). 82
Figure 6-1. Generalization of iterative investigation process. 86
Figure 6-2. General progressive or phased investigation approach. 88
Figure 6-3. In this example, an initial investigation was conducted to determine whether vapor-forming chemicals are present in exterior soil vapor near a commercial/industrial building. 90
Figure 6-4. Example of inadequate conceptual iterative sampling for a commercial/industrial building. 91
Figure 7-1. Example conceptual site model components and sampling locations displayed graphically. 96
Figure 7-2. Photographs showing how to screen soil for headspace measurements using a photoionization detector. These measurements can be collected from a glass jar covered in aluminum foil (left) or a baggie (right). 101
Figure 7-3. Examples of handheld screening devices for use in the field, including two photoionization detectors (top left and bottom left), two multi-gas meters (top center), a

flame ionization detector (bottom left-center), colorimetric gas detection tubes with pump (bottom right), and an MGD-2002 helium detector (top right). 102
Figure 7-4. Inficon Hapsite (top left), Defiant Technology's portable GC/frog (top center), proton transfer reaction mass spectroscopy system (top right), cavity ring-down spectroscopy system (bottom left), and automated continuous field gas chromatograph with stream selector valve and internet connection (bottom right). 103
Figure 7-5. Exterior (left) and interior (center) of a typical mobile laboratory, and a sample being injected into the mobile laboratory's gas chromatograph / mass spectrometer (right). 104
Figure 7-6. Active indoor air sample being collected using a passivated/evacuated canister. Note the placement in a bathroom (right) that contains multiple common preferential pathways. 106
Figure 7-7. Active outdoor air sample being collected using a passivated/evacuated canister. Note that canisters may require being secured from theft using a chain (right). 107
Figure 7-8. Passive air samplers deployed to collect indoor (left) and outdoor (right) air. 107
Figure 7-9. Active crawl-space sample collection using passivated canisters. 108
Figure 7-10. Passive crawl-space sample collection. 108
Figure 7-11. General schematic for installation of field-constructed sub-slab vapor probes. 109
Figure 7-12. General schematic for an installed preconstructed sub-slab vapor probe. 109
Figure 7-13. A photograph collage showing the installation process for a field-constructed sub-slab vapor probe (left) and a completed probe with compression fitting port (right). 110
Figure 7-14. Photographs of the installation process of a preconstructed sub-slab vapor probe (top), a complete preconstructed sub-slab vapor probe (bottom left), and a cross-section photograph for a preconstructed sub-slab vapor probe (bottom right). 111
Figure 7-15. Photograph (left) and diagram (right) of a driven soil vapor probe. 112
Figure 7-16. Diagram (left) and photograph (right) of a typical dual-nested soil vapor probe installed using the burial method. 112
Figure 7-17. Photographs of multi-nested (left) and triple-nested (right) soil vapor probes. Note that the probes on the right are temporary but were installed using the burial method. 113
Figure 7-18. Photographs of typical soil vapor probe implants. 114
Figure 7-19. Photographs of typical soil vapor probe tubing, including high-density polyethylene (left), Nylaflow (center), and Teflon (right). 114
Figure 7-20. Photographs of common materials used during the soil vapor probe installation process, including granular bentonite (top left), sand (top center), plastic three-way valves (bottom left and bottom center), compression valves (top right), compression fittings (center right), and a well box (bottom right). 115
Figure 7-21. Diagram (left) and photograph (right) of a typical passive soil vapor probe. 116
Figure 7-22. Examples of passivated stainless-steel canisters. 117
Figure 7-23. The left photograph shows examples of sorbent tubes used to collect air and vapor samples. The middle and right photographs show a TO-17 sorbent tube being sampled using a syringe and low-flow air pump, respectively. 118
Figure 7-24. Filling a Tedlar® bag using a syringe and three-way valve (top left); filling a Tedlar® bag using a vacuum chamber (sometimes called a lung-box; top right); a black Tedlar® bag, often used for sampling vapors that may be affected by light (bottom left); and a Kynar® bag (bottom right). 120
Figure 7-25. Transferring soil vapor sample from an air sampling bag into a 400 cc canister. The photograph on the right is a close-up image of the one on the left. 121
Figure 7-26. Gas-tight evacuated glass containers. 122

Figure 7-27. Examples of glass syringes used to collect soil vapor samples, often for analysis on a mobile laboratory (left) and a soil vapor sample being collected in a syringe (right). 122
Figure 7-28. Leak checking an evacuated canister prior to collecting an indoor/outdoor air sample. 124
Figure 7-29. Active outdoor (left) and indoor (right) air sample being collected using a pump and sorbent tube. 125
Figure 7-30. Purging a probe with a low-flow air pump (left) and a plastic syringe (right). 126
Figure 7-31. The photograph on the left shows soil vapor being purged at 200 mL/min. The photograph on the right shows a soil vapor sample being collected with a vacuum gauge between the probe and the sample container. 127
Figure 7-32. The left photograph shows a simple sampling train arrangement for a shut-in test using a syringe as the vacuum source. The right photograph shows a typical sampling train arrangement for a shut-in test when using a low-flow air pump as the vacuum source. 128
Figure 7-33. Performing a leak check on a soil vapor probe and sampling train using a liquid leak-check compound. Note the leak-check compound is in a baggie and placed next to the probe and sampling train at the ground surface. 129
Figure 7-34. The top photographs show examples of a laboratory-built soil vapor sampling shroud. The bottom photograph shows a field-constructed gas shroud over a soil vapor probe and sampling train. The system consists of shroud (clear bin), helium cylinder, field helium detector, and low-flow air pump for purging. 130
Figure 7-35. Diagram showing a proper sampling setup using a gaseous shroud. 131
Figure 7-36. Water dam used to leak check a sub-slab vapor probe. 133
Figure 7-37. Examples of passive soil vapor samplers. 135
Figure 7-38. Examples of passive indoor/outdoor air samplers. 135
Figure 7-39. Collecting a soil vapor sample from an existing groundwater monitoring well. 137
Figure 7-40. Photo of bad sample placement of indoor air samples. Note the adjacent drum with liquid at the bottom. 138
Figure 7-41. Depth versus concentration plot of O_2 and aerobically degradable compound concentrations. 145
Figure 7-42. Membrane interface probe tooling (left) and the receiver (right). 149
Figure 7-43. Grain-size distribution as shown after settlement during a shake test. 150
Figure 7-44. Visible light nonaqueous-phase liquid in soil after a shake test where red dye powder and water were added. 152
Figure 7-45. Diagram (left) of typical setup for collecting a passive sewer gas sample, photograph showing the collection of a passive sewer gas sample (top right), and a photograph showing the collection of an active sewer gas sample (bottom right). 154
Figure 7-46. P-trap sampling. 155
Figure 7-47. Vent stack sampling. 155
Figure 7-48. Photograph (left) and diagram (right) of a typical mass-flux chamber. 157
Figure 9-1. Basic steps in the iterative process of using a vapor intrusion model. 194
Figure 9-2. Comparison of modeled indoor air concentrations with biodegradation included (light blue) and neglected (dark blue) under conditions of varied foundation airflow. Results are from the BioVapor model. Nominal conditions include a 5-ft (1.5-m) source depth, 1 mg/L benzene, 10 mg/L dissolved total petroleum hydrocarbons, and sandy soil. 195
Figure 9-3. Example model results illustrating the effects of biodegradation on chemical concentrations reaching indoor air. Significantly lower indoor air concentrations occur for

both lower source vapor concentrations and at increased separation distance, as compared to model results that neglect biodegradation. Both three-dimensional and BioVapor model results are shown in a typical basement scenario for benzene. 198
Figure 11-1. Vapor intrusion pathway assessment process. 219
Figure 11-2. Component determination, exit points, and closure strategies. 220

LIST OF TABLES

Table 2-1. General differences between petroleum hydrocarbons and nonpetroleum hydrocarbons. 19
Table 3-1. Other concerns. 39
Table 3-2. Investigation and mitigation: impacts and concerns. 41
Table 6-1. Investigation medium overview and considerations. 88
Table 7-1. Sampling methods by media type / analyte / parameter. 98
Table 7-2. Detectors used in handheld gas detectors and/or portable vapor analytical instruments. 100
Table 7-3. Flow rates for sorbent tubes based on analytical method. 119
Table 7-4. Comparison of various leak detection compounds. 132
Table 7-5. Groundwater sampling methods for vapor intrusion investigations. 147
Table 7-6. Advantages and disadvantages of the various vapor intrusion investigative methodologies. 159
Table 7-7. Common analytical methods. 165
Table 8-1. Example lines of evidence to help distinguish between subsurface and background sources of vapor-forming chemicals in indoor air. 173
Table 8-2. Equations to calculate inhalation exposure. 188
Table 8-3. Equations to calculate potential inhalation risks and hazards that include exposure and toxicity. 190
Table 10-1. Vapor intrusion mitigation system fact sheets and technology information sheets. 207

CHAPTER 1: INTRODUCTION

Vapor-forming chemicals (VFCs) in soil and groundwater can volatilize into soil vapor and migrate through the unsaturated zone (vadose zone). Vapor intrusion (VI) occurs when these vapors migrate upward into overlying buildings through cracks and gaps in the building's floors, foundations, and preferential pathways (e.g., utility conduits, sewer lines), ultimately impacting indoor air. If VFCs are present at sufficiently high concentrations in the subsurface and migrate to indoor air, these vapors may pose a threat to the health and safety of building occupants This document also introduces the concept of direct volatilization where vapors are directly volatilized into the indoor air from a vapor source that has been released into the environment either through a conduit or where a vapor source has entered into a building.

VI is a potential human exposure pathway, meaning it represents a way for people to come into contact with hazardous vapors during their daily indoor activities (USEPA 2015c).

Each section of this document is designed to be fully self-contained, offering comprehensive information on specific topics. The information provided in **Chapter 2: Vapor Intrusion 101** offers an essential foundation for newer or less experienced practitioners to better understand the concept of vapor intrusion.

1.1. What Is the Purpose and Scope of This Document?

This document provides regulators, practitioners, responsible parties, and community members with consensus information based on empirical data and recent research to support VI decision-making under different regulatory frameworks. The VI assessment strategy described in this guidance document enables confident decision-making that protects human health for various types of VFCs. This document also provides a comprehensive methodology for screening, investigating, and managing potential VI sites.

The comprehensive VI topics described in this document enable confident decision-making that protects human health. The goal of this document is to provide best practices and most defensible approaches to each of these topics:

- **Chapter 2: Vapor Intrusion 101**
- **Chapter 3: Community Engagement**
- **Chapter 4: Conceptual Site Model**
- **Chapter 5: Site Screening**
- **Chapter 6: Iterative Investigation Process**
- **Chapter 7: Sampling and Analysis**
- **Chapter 8: Data Evaluation and Vapor Intrusion Risk Assessment**
- **Chapter 9: Modeling**
- **Chapter 10: Vapor Intrusion Mitigation**
- **Chapter 11:Vapor Intrusion Component Determination, Exit Points, and Closure**

In addition to the chapters and appendices, the Interstate Technology & Regulatory Council (ITRC) has put together a series of checklists, technology information sheets, and fact sheets on topics that offer

additional details or information. Though these documents are intended to be stand-alone documents, it is still important for the reader to also review the information in the main text that may provide additional information and context related to each subject.

This document does not cover emergency response actions related to VI and assumes that all emergency situations have been handled prior to consulting this text. If strong odors are detected, or combustible, explosive, or oxygen-deficient conditions may exist inside a building, then first responders should be contacted immediately.

1.2. Who Should Use This Document?

The primary audiences for this document are regulators and practitioners who evaluate and manage VI sites. This document also provides responsible parties, site owners, managers, community members and other stakeholders with a comprehensive understanding of the unique aspects of VI concepts.

1.3. Who Developed This Document?

The ITRC VI Update Team developed this guidance document. The team included more than 200 members from state and federal regulatory agencies, consultants, site owners (private and public sectors), academia, and community stakeholders. Many of these team members are recognized experts in the fields of VI. See the **Acknowledgments** for the complete VI Update Team roster.

It is essential to note that this guidance document is built upon three previous ITRC VI guidance documents: *Vapor Intrusion Pathway: A Practical Guidance* (2007 VI-1), *Petroleum Vapor Intrusion: Fundamentals of Screening, Investigation, and Management* (2014 PVI-1), and *Technical Resources for Vapor Intrusion Mitigation* (2021 VIM-1). These documents were the result of hundreds of additional professionals dedicating their time and resources to generate guidance documents that have served as the foundation of VI regulations and best practices since development.

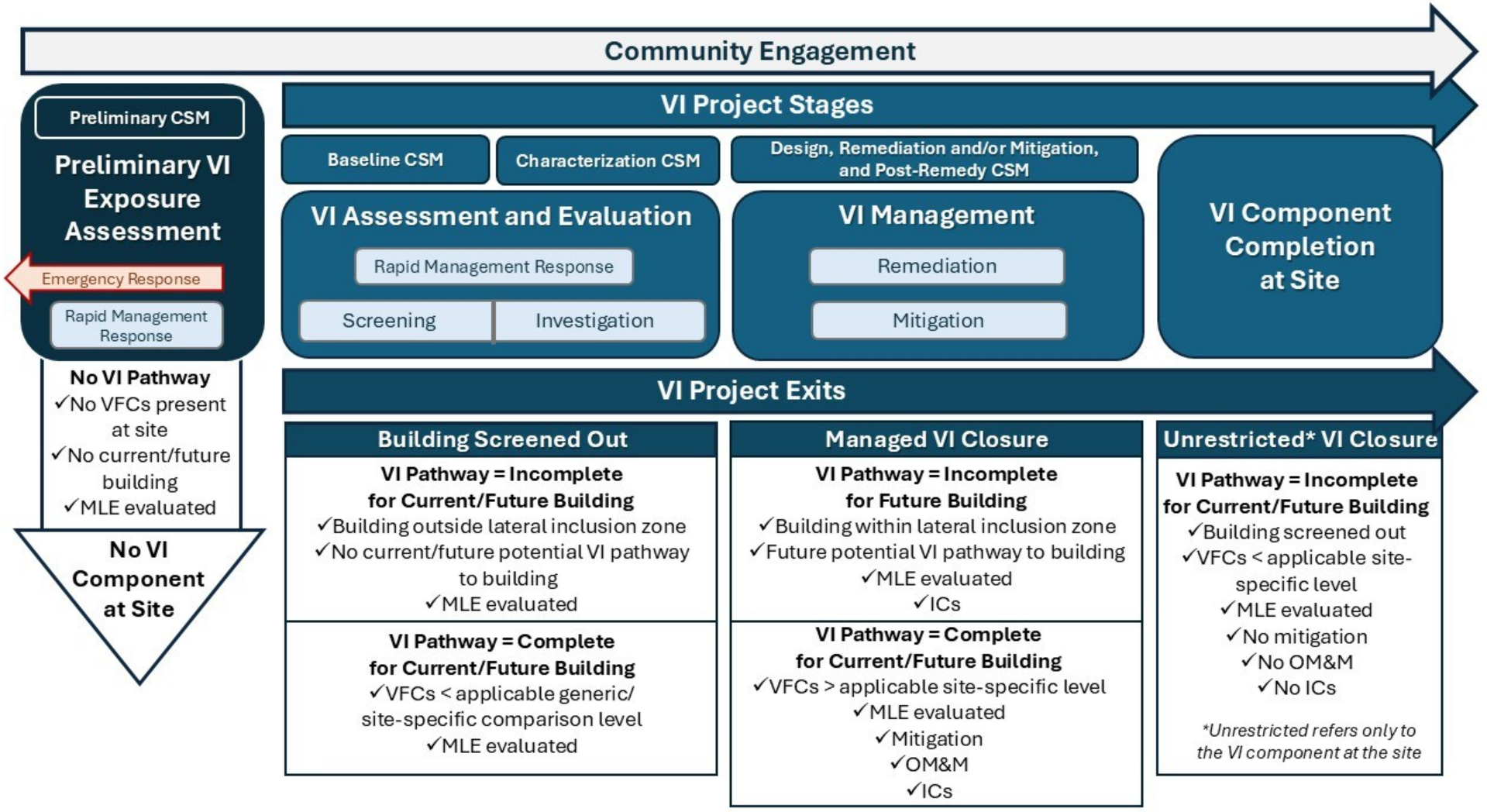
1.4. Why Is This Document Important?

State environmental regulatory agencies have consistently identified VI as a high priority to protect human health. ITRC has developed this document to update previous ITRC VI documents and provide a scientifically based, consensus approach to explain the following key issues for assessing and managing VI:

- What is VI and the direct volatilization to indoor air of vapors?
- How to perform an initial screen of a site.
- How to investigate VI.
- How to mitigate and manage the VI pathway.

1.5. What Is the Vapor Intrusion Strategy?

A consistent approach to VI that fits any regulatory framework and type of VI site is critical for confident decision-making that protects human health. **Figure 1-1** presents a consistent, flexible approach. This strategy is an iterative process, beginning with preliminary VI exposure assessment and development of a preliminary conceptual site model (CSM).



Note: CSM = conceptual site model; IC = institutional control; MLE = multiple lines of evidence; OM&M = operation, maintenance, and monitoring; VFC = vapor-forming chemical; and VI = vapor intrusion.

Figure 1-1. Vapor intrusion strategy flowchart.

This phase may be followed by a more detailed site investigation and refinement of the CSM or, if chosen, emergency or rapid response measures if conditions warrant. If a more detailed investigation is needed, depending on the outcome, site management for VI (such as vapor controls, long-term operation, maintenance, and monitoring [OM&M], and institutional controls [ICs]) may be required. In addition, community outreach is a critical component of the strategy that should be considered throughout the VI process.

Iterations within each of the strategy stages may be warranted and may overlap or occur concurrently with other ongoing stages, and investigators must decide whether to continue data collection and interpretation within a particular stage or to proceed to the next stage.

1.6. Overview of Vapor Intrusion Technical and Regulatory Guidance Chapters

Below are short introductions to each VI Technical and Regulatory Guidance chapters.

1.6.1. Vapor Intrusion 101 (Chapter 2)

VI 101 provides general information regarding the history of vapor intrusion and the evolution of the various guidance documents, discusses how vapor migrates through the subsurface, and other important VI considerations.

1.6.2. Community Engagement (Chapter 3)

It is important to engage the public at environmental contamination sites, but at vapor intrusion sites, it is essential to engage the people who own, live, work, or study in, or otherwise occupy impacted buildings. Their cooperation, not just permission, makes it possible to investigate, remediate, mitigate, and monitor properties contaminated or potentially contaminated with VFCs. The practitioner may be asking them to agree to allow intrusive or disruptive activities such as coordinating multiple entries, drilling holes through their floors, attaching fans and/or piping to their buildings, or rearranging rooms to accommodate investigatory/mitigatory activities. A successful outcome in which good decisions are made and stakeholders cooperate in the process requires building and maintaining trust.

1.6.3. Conceptual Site Models (Chapter 4)

The development of the VI portion of the CSM helps the practitioner evaluate the potential for a complete VI pathway, identify data gaps, and communicate findings and conclusions to other stakeholders based on the available data. The goal for developing a CSM in the assessment of the VI pathway is to assemble a three-dimensional concept of the site that is as comprehensive as possible. The CSM should present both a narrative and a visual representation of the actual or predicted relationships among the VFCs at the site and receptors (current and future building occupants), as well as reflect any relevant background concentrations.

1.6.4. Site Screening (Chapter 5)

Site screening is the initial phase in the VI assessment strategy for determining whether the VI pathway is potentially complete or not. The VI screening approach described in this guidance uses the three different concepts of screening to make this determination. It is achieved using one or more distance-based, concentration-based, or mass-flux-based approach. These are generally applied in a tiered manner, beginning with site screening based on distance, then concentration, and/or mass flux. It is important to

note that site screening is intended to be conservative, relying on conservative, default VI exposure assumptions that are meant to be protective of human health.

1.6.5. Iterative Investigation Process (Chapter 6)

When site screening cannot determine whether a site poses an unacceptable risk or cannot eliminate the need for further evaluation, some type of site investigation is employed to collect additional data or make a different evaluation to address data gaps in the CSM. Site investigation and site screening are linked and closely related. Often the moment when one process ends and the other begins can be a very fine line because once data are collected, a user must evaluate the data, which typically involves some type of screening process. Identifying key questions can support what type of data is needed to address any gaps or uncertainties, such as, Is VI occurring at the targeted building? or Are there background indoor air sources influencing indoor air at the targeted building? The key to site investigation is being able to collect sufficient data that allows a confident decision-making process, often using multiple lines of evidence (MLE).

1.6.6. Sampling and Analysis (Chapter 7)

The Sampling and Analysis chapter describes various sampling and analysis methods available for vapor intrusion investigations. This information will help you select the techniques that will best meet the data objectives for targeted media (i.e., soil vapor, sub-slab vapor, and air). In many cases, the methods and tools described in this section are applicable to both petroleum and nonpetroleum vapor investigations.

1.6.7. Data Evaluation and Vapor Intrusion Risk Assessment (Chapter 8)

This chapter assumes that site screening for the VI pathway determined that further data collection was warranted and that an investigation strategy was chosen, designed, and implemented. It provides a framework to evaluate the resulting data and describes approaches to assess VI risk, ranging from simply applying generic/default screening levels to conducting site-specific risk assessments. The goal of this process is to make a sound, technically defensible determination of whether the VI pathway is incomplete, potentially complete, or complete, and whether vapor mitigation or remediation may be necessary for the site.

1.6.8. Modeling (Chapter 9)

A modeling assessment is one of multiple optional methods applied in site investigation and evaluation. This chapter includes guidance on the application of VI models and steps to take for using a model, a summary of VI model types, and discussion on the differences between petroleum vapor intrusion (PVI) models and general VI models. The primary purpose of VI modeling is to estimate indoor air concentrations of VFCs based on soil, soil vapor, and/or groundwater concentrations.

1.6.9. Vapor Intrusion Mitigation (Chapter 10)

If the site screening or site investigation steps determine that the pathway is complete or likely complete, then mitigation of the VI pathway may be necessary. Management tools may include one or more options such as environmental remediation, ICs, and building mitigation. Regardless of the management tools used, the CSM should be refined and the VI pathway reevaluated as conditions change or new information becomes available.

1.6.10. Vapor Intrusion Component Determination, Exit Points, and Closure (Chapter 11)

VI project exit strategy will depend on the determination of a VI component, current and future site conditions/property use, and regulatory agency. Concluding a VI project at any stage of the VI life cycle requires understanding the presence of VFCs and the complex relationships among subsurface conditions (e.g., geology, utilities, groundwater, soil, soil vapor, etc.); incomplete, complete, or potentially complete VI pathways; and current/future buildings. A comprehensive approach is necessary to assess the intricate relationships among groundwater, soil, soil vapor, indoor air, pathways, and current/future building receptors prior to concluding the exit point (e.g., no VI component at a site, screening out a building, managed VI closure, or unrestricted VI closure). These evaluation methods can be used to make a sound, technically defensible determination as to whether or not the VI pathway is complete, potentially complete, or incomplete and warrants no further investigation; evaluate the potential risk associated with pathways that are found to be complete; and inform decision-making about next steps, such as further investigation, remediation, or mitigation. Some regulatory agencies may require additional periodic review or confirmation to ensure that the pathway remains incomplete over time.

1.6.11. References, Glossary, and Acronyms

This document includes a list of **acronyms**, a full **glossary**, and combined **references**. The user is encouraged to access each chapter and supplementary information and the most up-to-date source of information on this topic.

1.6.12. Acknowledgments

Though this section is not part of the investigative or decision-making process, it is through the work of these individuals, many of whom are considered industry experts and leaders in the field, that this document is possible. It is important to note that the contributions that were made in ITRC's earliest documents related to VI are in many ways still applicable today.

1.7. State Practices Survey

To support development of this document, the VI Update Team conducted a survey of state environmental regulatory agencies to gain insight into the state of the practice for addressing potential VI sites to build on the work by Eklund et al. (2024). Additional survey information to supplement the paper was collected in the spring of 2024 through state agency VI subject matter experts to gain additional insight into how each state is using existing VI guidance. Responses were provided from 49 states and the District of Columbia. **Appendix A: Summary of State Vapor Intrusion Practices**, provides a summary of the survey responses.

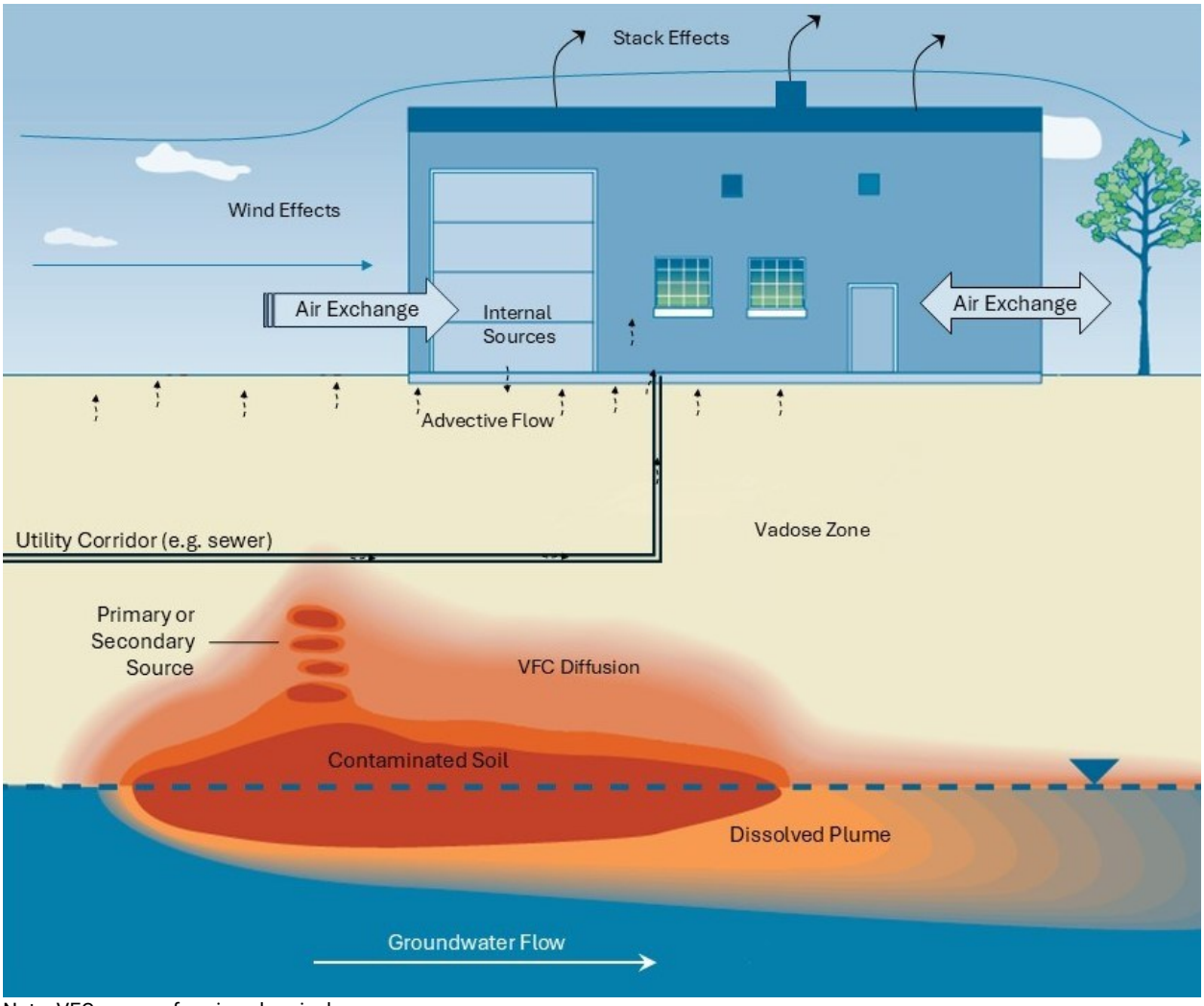
This portion of the page left blank intentionally. Next chapter starts on the following page.

CHAPTER 2: VAPOR INTRUSION 101

2.1. What Is Vapor Intrusion?

2.1.1. Definition of Vapor Intrusion

VFCs are volatile organic compounds (VOCs) in contaminated soil and groundwater that can volatilize into soil vapor and migrate through unsaturated soils in the vadose zone. VI occurs when these vapors migrate into overlying and nearby occupied or potentially occupied enclosed structures (hereinafter referred to as *buildings*) through cracks and gaps in the building floors, foundations, walls, utility conduits, and other pathways and contaminate indoor air. If present at concentrations above risk-based screening levels, these vapors may present a threat to the health and safety of building occupants. The VI pathway can be relatively complex depending on vapor source, subsurface conditions, and building conditions and use. The VI pathway is typically conceptualized as shown in Figure 2-1.



Note: VFC = vapor-forming chemical.

Figure 2-1. Conceptualized vapor intrusion pathway.

Chemicals that are sufficiently volatile and toxic may pose a health risk through the VI pathway. Regulatory agencies have different ways to define volatile chemicals for the VI pathway. Most states and regulatory agencies align with the U.S. Environmental Protection Agency (USEPA) which identifies VFCs as follows:

- Chemicals with a Henry's Law constant greater than 10^{-5} atm m^3 mol^{-1} at room temperature
- Chemicals with vapor pressure greater than 1 mm Hg at room temperature.

Vapor-Forming Chemicals

VFCs include chemicals that have volatilization potential. These may include the following:

- Volatile organic compounds
- Semi-volatile organic compounds
- Pesticide compounds
- Elemental mercury
- Per- and polyfluoroalkyl substances

Since the volatility of a compound is generally higher the lower its boiling point temperature, the volatility of organic compounds is sometimes defined and classified by their boiling points

VI is often considered if volatile chemical concentrations exceed certain screening levels. For example, the USEPA has developed Vapor Intrusion Screening Levels (VISLs) for VFCs that could potentially result in VI (USEPA 2017c) based on this definition. In addition, the indoor air concentration that would result from the maximum possible (pure phase vapor) concentration must be greater than the USEPA risk-based indoor air screening level to be considered sufficiently toxic and volatile to pose an inhalation risk. These chemicals may include chlorinated solvents, petroleum compounds, elemental mercury, select semivolatile organic compounds (SVOCs, such as naphthalene), and some polychlorinated biphenyls and pesticides (USEPA 2015d).

For the VI pathway to be complete, there must be three components—a source of VFCs in the subsurface environment (groundwater, soil vapor, and/or soil), occupied buildings or the potential for future inhabited buildings, and a migration route to connect them (as discussed above).

2.1.2. Evolution of Vapor Intrusion Science and Regulatory Guidance

The Love Canal disaster in New York in 1978 played a role in the early awareness of VI (USEPA 2013b). In that incident, chemical waste buried in the ground caused buried chemical waste to seep into nearby buildings and release toxic vapors that infiltrated homes and schools, leading to widespread health issues (Gibbs 1982). This event highlighted the need for more robust environmental policies addressing soil, water, and air contamination.

The 1986 Resource Conservation and Recovery Act (RCRA) Corrective Action Facility Assessment Guidance (USEPA 1986) included soil vapor sampling and subsurface gas characterization. In addition, the USEPA developed methods to address indoor air impacts at Superfund sites (USEPA 1992). The Brownfields Program, initiated in 1995, encouraged redevelopment of contaminated properties but required evaluation of VI risks in buildings constructed on or near such sites (Folkes and Arell 2001). By the mid-1990s, some states began requiring the evaluation and mitigation of VI exposure during environmental assessments. National awareness of the VI pathway for VOCs increased significantly around the year 2000. In 2002, USEPA published its first draft guidance addressing vapor intrusion, *Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathways from Groundwater and Soil* (USEPA 2002c), which brought VI and associated exposure pathways to the forefront of regulatory discussions. Subsequent revisions, including the *Technical Guide for Assessing and Mitigating the Vapor Intrusion Pathway from Subsurface Vapor Sources to Indoor Air* released in 2015, have refined assessment techniques and mitigation strategies to better protect public health (USEPA 2015c).

The ASTM International, formerly known as the American Society for Testing and Materials (ASTM) recognized VI as an integral component of its standards. In 2010, it published the *Vapor Encroachment*

Screening Standard (E2600-10), (ASTM International 2015) followed in 2013 by the *Phase I ESA Standard (E1527-13)* (ASTM International 2021). These standards provided frameworks for identifying and managing VI risks during property transactions and environmental assessments.

During the 2000s, some states began developing their own guidance on VI. Beginning in the 2010s, USEPA expanded the number of publications related to VI. Notable publications included the "EPA Region 9 Response Action Levels and Recommendations to Address Near-Term Inhalation Exposures to TCE in Air from Subsurface Vapor Intrusion Memo" (2014) and the "EPA VI Database Published Study" (USEPA 2012b). These documents laid the groundwork for states to develop and refine their own guidance, often tailored to regional needs and updated as scientific understanding advanced. Federal guidance also emphasized the importance of differentiating between VI types, such as chlorinated VI and PVI.

When the USEPA published its draft VI guidance in 2002, it included a disclaimer stating it was not intended for use at underground storage tank (UST) sites regulated under Subtitle I of the Solid Waste Disposal Act. This gap was addressed in 2015 with the release of the *Technical Guide for Addressing Petroleum Vapor Intrusion at Leaking Underground Storage Tank Sites*, a companion to the broader VI Technical Guide released in 2015 by the Office of Solid Waste and Emergency Response (OSWER), which replaced the 2002 draft guidance. OSWER is now known as the Office of Land and Emergency Management. In addition, regional USEPA offices developed specific guidance pertaining to their specific regions. USEPA Region 1 (Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont) released their "Vapor Intrusion Guidance for Contaminated Sites" in 2008, which has been retired and replaced with current USEPA guidance. USEPA Region 5 (Illinois, Indiana, Michigan. Minnesota, Ohio, and Wisconsin) released the "Region 5 Vapor Intrusion Handbook" (USEPA 2020) in March 2020.

Besides the USEPA, the U.S. Department of Defense's (DOD's) Tri-Service Environmental Risk Assessment Work Group released the *DOD Vapor Intrusion Handbook* in 2009 to serve as a resource for investigating the VI pathway at DOD sites (USDOD 2009). ITRC published its first VI guidance in 2007, titled *Vapor Intrusion Pathway: A Practical Guidance* (ITRC 2007). This document offered a logical, flexible framework for assessing VI complemented by case studies, tools, and remedial approaches. Building on this foundation, ITRC released *Petroleum Vapor Intrusion: Fundamentals of Screening, Investigation, and Management* in 2014 (ITRC 2014), focusing specifically on PVI sites contaminated with petroleum hydrocarbons.

In 2020, ITRC developed the VI mitigation team's fact sheets, technology information sheets, and checklists to provide a web-based approach to VI mitigation. These resources offered practical tools for regulators and stakeholders managing VI risks.

Many states have developed and updated their own guidance documents and regulations, addressing screening levels, VI and PVI assessment, and mitigation strategies. These approaches often vary by state and are described in **Appendix A: Summary of State Vapor Intrusion Practices** (Eklund et al. 2024). Responsible parties, consultants, and other stakeholders must identify the relevant jurisdictional authorities and comply with applicable regulations and guidance.

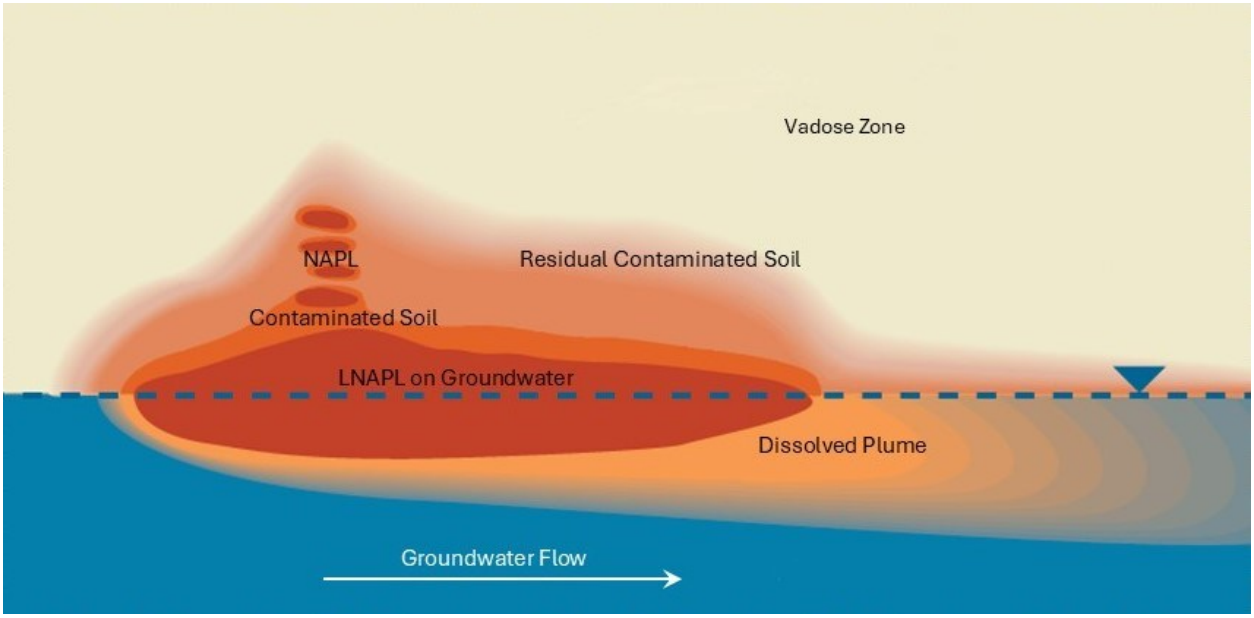
This ITRC guidance consolidates and updates previously published ITRC guidance related to VI. Upon publication, earlier ITRC guidance documents will be archived. This guidance aims to streamline VI assessment and mitigation efforts by consolidating decades of regulatory advancements and best practices. By integrating state and federal guidance, stakeholders can better address the evolving challenges associated with VI, ensuring public health and environmental protection. Responsible parties, their consultants, and other stakeholders should always determine which agencies have jurisdiction at VI or PVI sites and follow applicable regulations and guidance. This ITRC document is intended to provide technical support and resources but does not supersede applicable regulations and guidance.

2.1.3. Vapor Transport

Transport of VFCs from sources to buildings typically begins with partitioning of the VFC molecules from the source medium, followed by diffusion of the molecules to locations with lower concentrations and diffusion and/or advection into buildings, as described below.

2.1.3.1. Sources of Vapor-Forming Chemicals in Soil Vapor

Sources of VFCs in the soil vapor include VFC-contaminated groundwater (at the water table), contaminated soils in the vadose zone, and nonaqueous-phase liquids (NAPL) including light NAPL (LNAPL) and dense NAPL (DNAPL) above the groundwater table (Figure 2-2). VFC molecules partition from the water, soil, and/or NAPL phases into unsaturated voids in the vadose zone, or the soil vapor phase. The potential concentrations in the soil vapor phase at equilibrium immediately adjacent to the VFC source medium can be estimated by Henry's Law for partitioning from the water to air phase and by Raoult's Law for partitioning from the nonaqueous phase to the air phase. Actual concentrations under steady-state conditions may be lower than theoretical equilibrium values for a variety of reasons, including attenuation in the capillary fringe above the water table.



Note: LNAPL = light nonaqueous-phase liquid, NAPL = nonaqueous-phase liquid.

Figure 2-2. Sources of vapor-forming chemicals.

Several factors can affect the subsequent transport of vapors from the subsurface source zone to indoor air. In most cases, diffusion of the VFC molecules is the primary transport mechanism from the source to locations with lower concentrations, followed by diffusion and/or advection (soil vapor flow) into the building (Ma et al. 2020). In rare cases, high VFC concentrations in relatively permeable deposits can result in downward advective movement due to density differences, for example, when vapors result from shallow releases of DNAPL (USEPA 2012a). Diffusion and advection transport mechanisms are discussed in further detail below, including advective transport in open conduits (preferential pathways).

2.1.3.2. Diffusion Transport

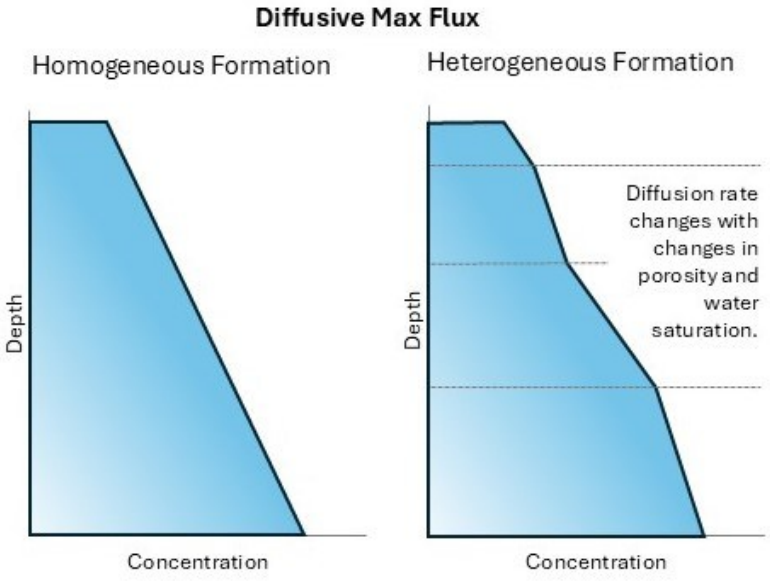


Figure 2-3. Diffusive transport.

Diffusion is the natural movement of a chemical from an area of higher concentration, such as in the VFC source zone, to an area of lower concentration, such as the vadose zone away from the source (Figure 2-3). Depending on the location of the source (at depth, near the surface, or within the vadose zone), VFC molecules may diffuse in all directions, including upward, downward, and laterally. VFC molecules will also diffuse laterally toward areas with lower concentrations, potentially impacting buildings that are near but not directly over the source. Diffusion is typically the dominant transport mechanism for VFCs in soil vapor except in regions close to building foundations or when preferential pathways create open conduits for vapor flow between sources and buildings (Beckley and McHugh 2020). Additional discussion can be found in the Vapor Intrusion Preferential Pathways Fact Sheet.

Fick's Law

$$J = -D\frac{d\varphi}{dx}$$

Where:

J = diffusion flux

D= diffusion coefficient

dφ = change in concentration

dx = change in position

$\frac{d\varphi}{dx}$ = concentration gradient

The diffusive mass flux of VFC molecules in soil vapor is described by Fick's law (see the equation in the adjacent text box) and is directly proportional to the vapor concentration gradient; therefore, larger gradients result in greater diffusive flux. In addition to the concentration gradient, the effective diffusion coefficient of the soil, which is a function of total porosity and the degree of water saturation or effective porosity, also affects the rate of the diffusion through the vadose zone. While diffusion occurs in both the aqueous and vapor phases, the diffusion coefficients of VFCs in water are typically about four orders of magnitude lower (i.e., slower) than the diffusion coefficients in air; therefore, as the soil becomes more saturated, diffusion coefficients and VFC flux decrease. Therefore, the capillary fringe (referring to the thickness of the body of saturated water held by capillary action that fills the pore space directly above the water table; Section 2.2.7.1) can often reduce the overall vapor diffusive flux from groundwater to ground surface. Conversely, dry soils provide more air-filled pore spaces that allow for higher rates of diffusive transport as compared to saturated soil.

Although the diffusive flux will depend in part on the effective diffusion coefficient of the soil, as described above, the vapor concentration profile will vary linearly from the source to the location of concern (such as the bottom of a basement slab) in all homogeneous soils, as shown in Figure 2-3. In nonhomogeneous or layered soils, concentrations will reduce (or attenuate) more rapidly with distance in the layers with lower effective diffusion coefficients, as shown in Figure 2-3. Work presented by Carr (2010) illustrates how layers of saturated fine-grained soils are associated with steeper concentration gradients and, therefore, significant reductions in the soil vapor concentration with distance above the source.

VFC molecules in soil vapor immediately adjacent to a building can continue to diffuse from the soil into the building—for example, from dirt floors in basements or crawl spaces or through cracks and other discontinuities in floor slabs and foundation walls. VFC molecules can also diffuse through concrete and other building materials (including vapor barriers or other materials), but the diffusion coefficients and rates of diffusion through these materials are generally small (particularly for vapor barrier materials intended to control diffusion), as discussed below. Nevertheless, when VFC concentrations adjacent to a slab or foundation wall are particularly high and/or the concrete is significantly degraded, the diffusion flux can be high enough to be of concern. See **Chapter 10: Vapor Intrusion Mitigation** for more information on how diffusion can influence mitigation and remediation decisions.

2.1.3.3. Advective Transport

Advection is the transport mechanism by which soil vapors move due to differences in air or soil vapor pressure between locations, such as in vadose soils and the overlying indoor air space of buildings. Any VFC molecules in the soil vapor are transported with the soil vapor into the building. These pressure differences can be generated by atmospheric pressure changes; wind loads; or the *stack effect*, which is forced pressure changes due to exhaust fans and other building ventilation systems. Advective transport of soil vapor in the subsurface is likely to be the most significant in the region very close to a basement or a foundation; soil vapor velocities decrease rapidly with increasing distance from the building (USEPA 2017a).

Stack Effect

The stack effect occurs when the internal air pressure is lower than the pressure in the subsurface, creating a vacuum effect. The stack effect may be created by heating systems, exhaust fans, or strong winds that reduce pressures above openings due to the Bernoulli effect.

Once VFCs diffusing in soil vapor through the subsurface are close enough to the building for pressure gradients to cause advective flow of soil vapor, they can be swept with the soil vapor into the building air. Soil vapor entry points through concrete slabs may include cracks, expansion joints, floor drains, and sumps, as well as the annular spaces around utility penetrations and other openings or discontinuities in the floor and foundation walls (**Figure 2-4**). Soil vapor entry points may not always be visible due to small size or coverings like flooring or wall cavities.

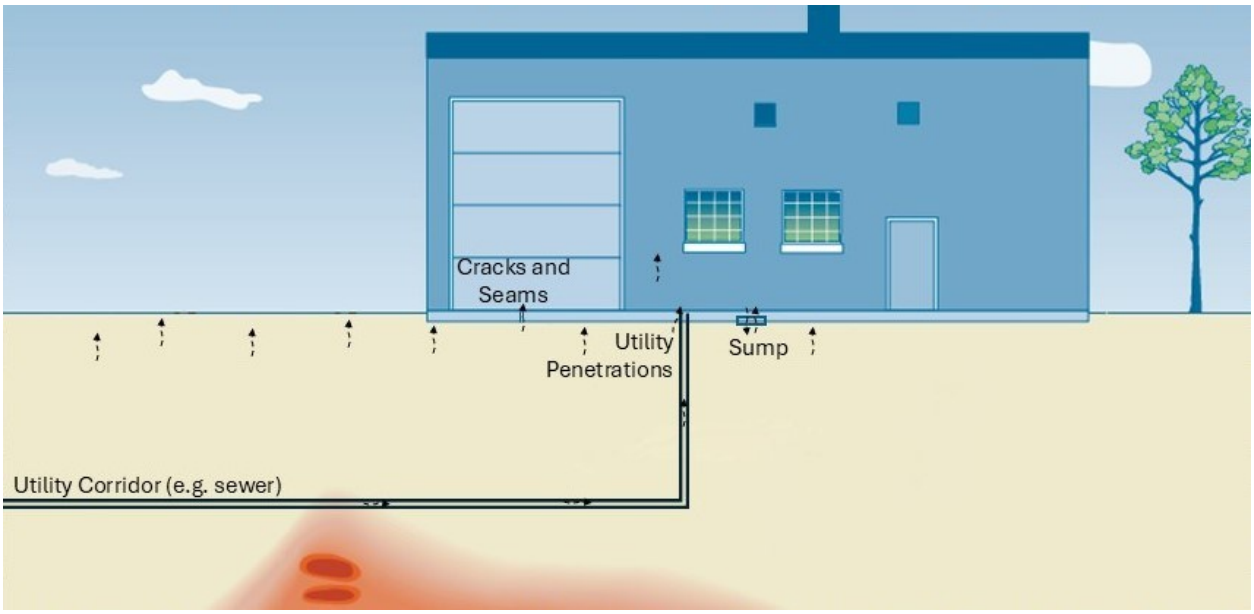


Figure 2-4. Advective transport.

Typically, pressure differentials between the building and the subsurface are relatively small (USEPA 1993b), so the zone of influence of the pressure fields associated with building-induced advective flow does not extend far beneath or around the base of the building. Pressure gradients can differ based on building construction; for example, the stack effect may be more significant for taller buildings. Pressure gradients may also fluctuate for a variety of other reasons, such as heating, ventilation, and air conditioning (HVAC) operations, barometric pressure changes, and open windows. The rate of movement of the vapors into the building is a difficult value to quantify and depends on soil type, chemical properties, building design and condition, the pressure differential, and the rate of change in pressure differential.

2.1.3.4. Dilution in Building Air

Soil vapor that enters a building from the subsurface mixes with the building air, through diffusion of the VFCs within the indoor air space and movement of the building air due to natural and/or mechanical ventilation. This dilution of the vapor concentrations in the building air is a function of the building air volume and ventilation rate or air exchange rate (Figure 2-5). HVAC operations can also exacerbate vapor intrusion impacts by moving air from unoccupied areas, such as a building crawl space, to other occupied areas of the building.

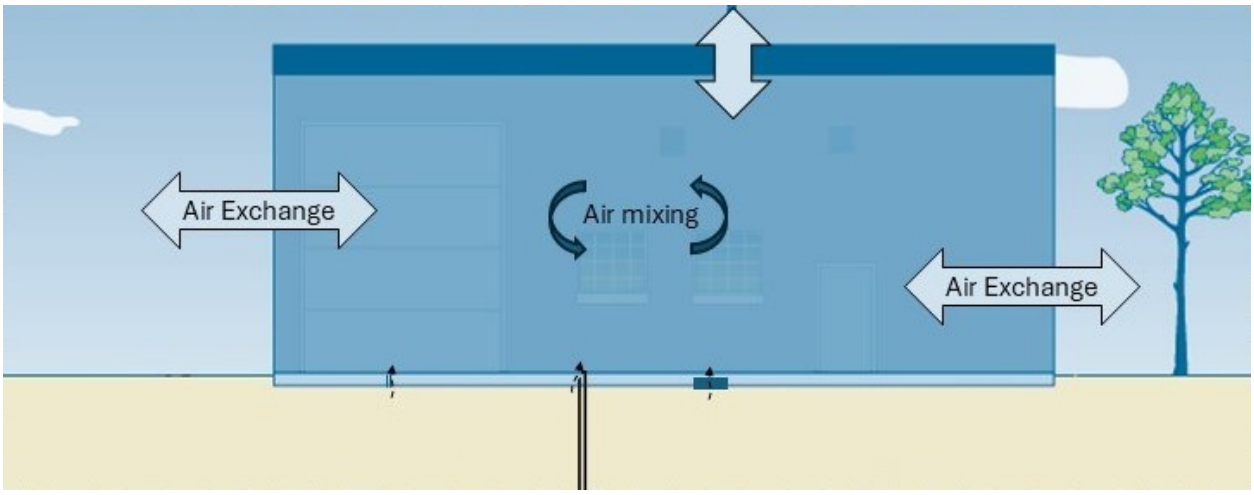


Figure 2-5. Dilution of soil vapor in indoor air.

2.1.3.5. Attenuation Factor

The amount of vapor attenuation/dilution from the subsurface media concentration to the indoor air concentration is known as the *attenuation factor* (AF) (Johnson and Ettinger 1991). AFs are used in several ways when evaluating the potential for VI, including the development of screening levels based on empirical or modeled predictions of attenuation from groundwater and/or soil vapor sources and the evaluation of the potential for indoor air impacts at specific sites. The AF is the ratio of the indoor air concentration to the soil vapor concentration at a specific depth, such as in deep soil vapor, shallow soil vapor (beneath or adjacent to the building), or sub-slab soil vapor (immediately beneath the building slab). Therefore, AFs should always be identified by the location or depth of the applicable soil vapor concentration. More information is provided in the Attenuation Factors Fact Sheet.

Groundwater-to-Indoor Air Attenuation Factor

This is a dimensionless ratio used to estimate how much a contaminant concentration in indoor air is reduced relative to its concentration in underlying groundwater. It accounts for the processes that reduce contaminant levels as vapors migrate from groundwater, through the vadose zone (unsaturated soil), and into the indoor air of overlying buildings.

The groundwater-to-indoor-air AF is typically based on a soil vapor concentration, which is equal to the groundwater concentration at the water table multiplied by the Henry's Law coefficient (HLC) of the VFC and expressed in the same units as the indoor air concentration (the groundwater concentration should be converted to a soil vapor concentration using the HLC and not used directly in the groundwater AF calculation). It should be noted that the HLC assumes equilibrium between the water and vapor phase, which is not always the case. Further, for practical reasons soil vapor samples must be collected above the capillary fringe where the air content of the pore space is sufficiently high to collect a water-free sample; therefore, some attenuation may have occurred between the water table and the soil vapor sample collection depth, resulting in a concentration that will be lower than the Henry's Law equilibrium concentration.

Because AFs are the ratio of the indoor air to subsurface concentrations, the AF for VI scenarios should in theory always be less than or equal to 1.0 and is typically orders of magnitude smaller than 1.0. The smaller the AF, the greater the amount of attenuation of the soil vapor concentration.

2.2. Important Vapor Intrusion Considerations

2.2.1. Regulatory Considerations

Federal, state, and local policies, regulatory requirements, and guidance vary and may result in different approaches even in otherwise similar settings. Regulatory policies, guidance, and requirements may offer specific approaches and screening levels for the evaluation of the VI pathway, and some jurisdictions may provide guidance that is not recognized in other jurisdictions (**Appendix A: Summary of State Vapor Intrusion Practices**).

An example of varying regulatory requirements are requirements for evaluating the VI pathway for existing construction (i.e., residential, commercial, or industrial buildings) versus requirements for evaluating the VI pathway for future land uses (i.e., vacant land). Evaluation of the VI pathway for future land uses is discussed in greater detail in **Section 4.2.2**.

2.2.2. Community Engagement

Investigations at VI sites can be disconcerting and intrusive into the lives of individual stakeholders and communities, who may have little technical knowledge about the issues confronting them. Rather than addressing an adjacent or outdoor location, VI directly affects the places in which people live and work. Investigations and mitigation require active cooperation among building occupants and owners. These stakeholders may have concerns related to VI, in addition to concerns typical of other types of environmental investigations. For this reason, outreach and risk communication may require more attention than other environmental projects.

Community outreach and risk communication at VI sites is, with a few exceptions, similar to outreach efforts for other environmental projects. VI requires effective education of the affected community regarding the risk of soil vapor migrating from the subsurface as well as background sources typically found in the building.

Be Prepared for Questions

Regulators, project managers, and others involved in community engagement should be prepared to address VI concerns and questions that are likely to arise during any phase of investigation, mitigation, or remediation.

2.2.3. Emergency and Rapid Response Situations

2.2.3.1. Chronic vs. Acute Exposure

In most cases, VI investigations are concerned with chronic exposure, which occurs at relatively low levels over a long period of time; however, in some cases VI investigations may include concern for short-term or acute exposure to the chemicals of concern (COC). Acute exposures can range in severity and may cause immediate apparent health effects or present physical hazards such as explosive vapors. Acute emergency situations such as explosive vapors or strong odors should be addressed as emergency response conditions before beginning or continuing a VI investigation (see **Section 5.2.3 Evaluation of Emergency or Rapid Response**). A VI investigation may be concerned with both acute and chronic exposure, and conditions may change exposure over time.

Exposure to a volatile chemical due to VI does not necessarily mean that health effects will occur. Whether or not a person experiences health effects depends on several factors, including the length of exposure, the amount of exposure, the frequency of exposure, the toxicity of the volatile chemical, and the individual's sensitivity to the chemical. The main concern is whether the chemicals may pose an unacceptable risk of chronic health effects due to long-term exposure. It should be noted that the VI pathway may not be the only complete pathway for a particular receptor.

More information regarding risk assessment can be found in **Section 8.6 Site-Specific Risk Assessment**.

2.2.3.2. Emergency Situations and Explosive Conditions

Where there are obvious signs of odors or explosive hazards, these potential risks should be addressed immediately. Explosive conditions exist when the concentration range of the vapor is between the lower explosive limit (LEL) and the upper explosive limit (UEL).

For probable chronic exposure, the site may be evaluated on either a generic or site-specific basis in a timely manner. There may be precluding factors that limit using a generic screen (e.g., wet basements, sumps).

Emergency (911) Situations

This document does not cover emergency response actions related to VI creating a combustible, explosive, or other hazardous environment.

If strong odors are detected or there is reason to believe that combustible, explosive, oxygen-deficient, or toxic condition exists inside a building, immediately evacuate the building and contact first responders.

2.2.4. Background Sources of Chemicals

Indoor air often contains measurable concentrations of volatile and semivolatile compounds from sources that are not related to the VI pathway (typically called *background sources*). Examples of background sources of VFCs in indoor air include the following:

- Outdoor air (sometimes referred to as ambient) quality
- Vapors off-gassing from tap water
- Off-gassing from household or commercial products stored or used in a building
- Off-gassing from building materials containing VFCs
- Use of products containing VFCs during household activities
- Off-gassing from recently dry-cleaned clothes

- Exhaust from operating internal combustion engines within buildings (e.g., cars in garages), or outside of buildings but near air intakes or openings in buildings

As a result of the presence of background sources, attribution of chemicals in indoor air to VI can become a relatively complex and difficult task. The presence and effects of background indoor air sources will likely be one of several lines of evidence (LOEs) that may be evaluated as part of a VI investigation. Additional information on background sources of chemicals can be found in the **Background Sources to Indoor Air Fact Sheet**. Background indoor air sources may be considered an LOE in what is called an MLE approach as discussed in the **Multiple Lines of Evidence Fact Sheet**.

2.2.5. Spatial and Temporal Variability

Indoor air concentrations due to VI can vary substantially between buildings overlying or near a vapor source such as impacted soils or groundwater plume. This is due to spatial variations in source concentrations and distance, subsurface conditions affecting soil vapor migration, and/or building and HVAC conditions affecting the rate of soil vapor entry and dilution within the building. Subsurface concentrations of VFCs in soil vapor can exhibit substantial spatial variability due to variations in groundwater (or vadose-zone source) concentrations, heterogeneous geological and moisture conditions, anthropogenic features (creating preferential pathways or barriers), and other factors that may be specific to an individual site (Folkes et al. 2009; USEPA 2015c). Similarly, the resistance of building foundations to vapor entry and indoor air pressures that might drive or impede vapor entry can vary substantially between buildings or portions of larger buildings. The potential for spatial variability may affect decisions regarding which buildings to test in areas where multiple buildings may be impacted (e.g., a neighborhood) and sampling locations for a specific building (e.g., soil vapor samples below a building or slab versus close to but outside the building).

Indoor air concentrations due to VI can also vary substantially over time due to temporal variations in source concentrations and soil moisture contents (i.e., varying effective diffusion coefficients), seasonal and short-term variations in factors that drive advective flow of soil vapor into buildings (barometric pressure changes, stack effect due to indoor versus outdoor temperature difference, wind effects, operation of exhaust fans), and variations in factors that affect the dilution of VFCs in indoor air (i.e., the indoor air exchange rate), such as opening and closing of windows and doors and operation of HVAC systems. Empirical data at VI and radon sites have indicated that indoor air concentrations typically range by a factor of 2 to 3 (e.g., Folkes et al. 2009). In the absence of a significant preferential pathway, the highest concentrations typically (but not always) occur in cooler weather. To assess temporal variability, many regulatory agencies recommend sampling in different seasons. Sample collection may also be biased toward times or conditions that are more conducive to VI, such as during winter and/or when the building is naturally or mechanically depressurized (see **Section 2.1.3.3**). The results of sampling under these conditions may be conservative in that they may overestimate mean concentrations or, in the case of induced negative building pressures, represent worst-case conditions or conditions not likely to occur.

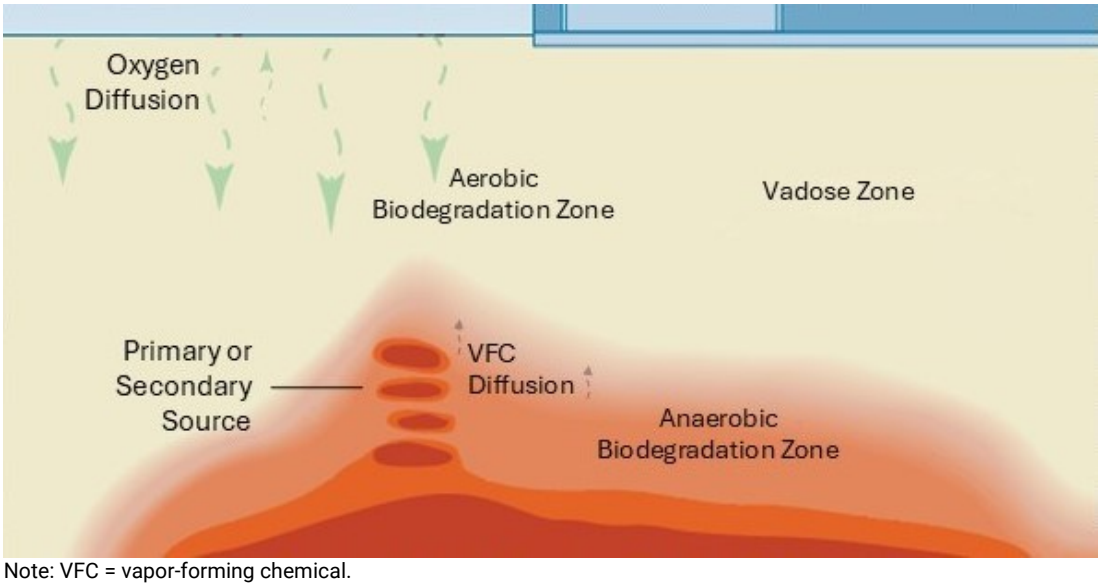
Assessments and investigations of VI should also consider the time required for soil vapor concentrations to achieve steady-state concentrations after a change in site conditions. For example, it will take time for VFCs to diffuse back into the void space created by the installation of a sampling probe and to reestablish concentrations that were present before the ground was disturbed, although purging of the probe and sample tubing can reduce the time required. At the lower boundary of the vadose zone, it may take weeks or months for soil vapor concentrations to reach steady-state concentrations in the vadose zone after a groundwater plume (vapor source) first arrives below a building or after the source is remediated (Johnson et al. 1999). At the upper boundary of the vadose zone, an active mitigation system (see **Section 2.4.2**) will typically reduce sub-slab vapor concentrations over time until the vapor concentration profile and the resulting upward diffusion mass flux achieves equilibrium with the mass flux of the mitigation system (Folkes and Sanpawanitchakit 2011). Similarly, when an active mitigation system is turned off, it will take time for sub-slab vapor concentrations to rebound to the higher levels

consistent with initial conditions (unless vapor concentrations in the vadose zone have been reduced due to source remediation or depletion). Therefore, sampling to confirm that mitigation is no longer required must consider the time required for rebound, if any, to occur.

The potential for spatial and temporal variability in subsurface and indoor air concentrations should be addressed by collection of sufficient data to assess the impact of variability on data collection (see Chapter 7: Sampling and Analysis), evaluation (see Chapter 8: Data Evaluation and Vapor Intrusion Risk Assessment), and site management decisions (see Chapter 10: Vapor Intrusion Mitigation).

2.2.6. How Is Petroleum Vapor Intrusion Different from Nonpetroleum Vapor Intrusion?

PVI is a subset of VI and is the process by which volatile petroleum hydrocarbons (PHCs) and other aerobically degradable VFCs (e.g., petroleum additives such as 1,2-dichloroethane and 1,2-ethylene dibromide [EDB]) (Davis, Patterson, and Johnston 2009; McKeever et al. 2012; Patterson et al. 2013) are released as vapors from LNAPL, petroleum-contaminated soils, or petroleum-contaminated groundwater that migrate through the vadose zone and into overlying buildings. Fortunately, in the case of PHC vapors, this migration is often limited by microorganisms that are normally present in soil. The organisms consume these chemicals, reducing them to nontoxic end products through the process of biodegradation. The extent and rate to which this natural biodegradation process occurs is strongly influenced by the concentration of the vapor source, the distance the vapors must travel through soil from the source to potential receptors, and the presence of oxygen (O2) in the subsurface environment between the source and potential receptors. The behavior of aerobically degradable VFCs in soil vapor can be substantially different from the behavior of nonpetroleum VFCs (e.g., chlorinated solvents). Some nonpetroleum VFCs, such as vinyl chloride, behave like PHCs in that they can be aerobically degraded. This can affect the amount of attenuation that occurs between vapor source zones and buildings, the applicability of screening levels based on AFs (USEPA OUST 2015), the potential for VI, and the need for and type of vapor control or mitigation. The potential for explosive concentrations of aerobically degradable VFC vapors, which is rarely an issue for nonpetroleum compounds, must also be considered. Methane can be produced at petroleum release sites due to anaerobic conditions. In addition, ethanol-based fuels can pose a greater concern for methane generation due to ethanol's high oxygen content. The ASTM provides a *Standard Guide for Evaluating the Potential Hazard as a Result of Methane in the Vadose Zone* (E2993) (ASTM International 2023).



Note: VFC = vapor-forming chemical.

Figure 2-6. Biodegradation.

Biodegradation

PHC-degrading bacteria are found in nearly all environments and can consume hydrocarbons rapidly in the presence of O2. This activity can limit transport and VI effects of PHC vapors.

The defining feature of PVI that distinguishes it from other types of VI is the relatively rapid rate of attenuation of aerobically degradable VFC vapors because of aerobic biodegradation in vadose-zone soils (USEPA OUST 2015) (**Figure 2-6**). Evaluation (Davis 2009; Lahvis et al. 2013; USEPA 2013c) of empirical soil vapor data have demonstrated that biodegradation can limit the migration of aerobically degradable VFC vapors from a subsurface source. This includes petroleum VFCs such as benzene, but also other chemicals such as lead scavengers (e.g., Kolhatkar et al. 2019; 2021; Wozney et al. 2022). These studies indicate that the potential for PVI is reduced because biodegradation minimizes the flux of aerobically degradable VFC vapors in soil vapor from a source to overlying buildings. Although PVI may be possible under certain environmental conditions, McHugh et al. (2010, 726) note that "the most common cause of PVI is dissolved PHCs or LNAPL in direct contact with building structures such as sumps, basements, or elevator pits." For more information see the **Direct Volatilization to Indoor Air Fact Sheet**.

Table 2-1 summarizes key differences between PVI and VI. Much of the information is presented in *Petroleum Hydrocarbons and Chlorinated Hydrocarbons Differ in Their Potential for Vapor Intrusion* (USEPA 2012e). These differences form the basis for the PVI-specific site screening approach, as detailed in **Appendix F: Distance-Based Screening at Petroleum Vapor Intrusion Sites**.

Understanding and properly characterizing the petroleum source is important for PVI. The petroleum source encountered can be broadly categorized as gasolines, middle distillates, and residual fuels, with the middle category including diesel, kerosene, Stoddard solvent, and some types of jet fuels (API 1994). The detailed chemistry of petroleum fuels has been extensively studied (Potter and Simmons 1998; USEPA 2009). These fuels are primarily composed of hundreds of nonspecific, aliphatic (straight-chain) hydrocarbon compounds with a small, variable amount of aromatic (having a benzene ring) compounds, including benzene, toluene, ethylbenzene, and xylenes (BTEX) and naphthalene. Collectively, all these hydrocarbons are referred to as total petroleum hydrocarbons (TPH). The vapors associated with petroleum fuels are similarly dominated by aliphatic compounds with smaller amounts of aromatic compounds (Brewer et al. 2014; USEPA 2013c). The actual vapors above the petroleum source will depend on the chemical composition of the vapor source, vapor pressures of the chemicals, and temperature. In commingled plumes (containing both PHCs and nonpetroleum VFCs), nonpetroleum VFCs can be present in the LNAPL as well, occurring above the water table.

Table 2-1. General differences between petroleum hydrocarbons and nonpetroleum hydrocarbons.

Property	PHCs	Non-PHCs	PVI-related details
Distribution in Groundwater	A significant portion of the source mass can reside above the water table as LNAPL.	Most free-phase product (DNAPL) migrates below the water table to a less penetrable layer. Note: in commingled plumes (plumes containing both PHCs and other VFCs) the other VFCs can be present in the LNAPL (above the water table).	• LNAPL will be mostly above groundwater and spread with changes in groundwater elevation. • Risk of PVI generally decreases when only dissolved phase is present. • Length of dissolved-phase plumes is typically limited by biodegradation.
Biodegradation	Primarily aerobic and relatively rapid; bio-degradation interface is small (from a few inches up to 5 or 6 feet).	Primarily anaerobic (except vinyl chloride); relatively slow; generally limited to anoxic zones.	• O_2 in soil and water will promote biodegradation. • Biodegradation will limit the size of the PHC vapor plume in the vadose zone. • Biodegradation will occur rapidly over a short distance in the presence of >2% O_2 in soil vapor. • Atmospheric O_2 replenishment in the vadose zone is usually sufficient to continually support biodegradation. • Lack of O_2 (<2% O_2 in soil vapor) causes the following: o Significantly decreases biodegradation rate o Extends the distance vapors can travel before being biodegraded • May promote production of methane
Biodegradation Products	Aerobic conditions: carbon dioxide (CO_2) and water. Anaerobic conditions: methane and carbon monoxide (CO).	Degradation chemicals may be more toxic.	• Terminal biodegradation products are nontoxic. • Methane is a potential explosion hazard in presence of ignition sources. • Methane production is generally increased by the presence of ethanol in fuels.

Notes: DNAPL = dense nonaqueous-phase liquid, LNAPL = light nonaqueous-phase liquid, PHC = petroleum hydrocarbon, PVI = petroleum vapor intrusion, and VFC = vapor-forming chemical.

Source: USEPA (2012e).

2.2.6.1. Environmental Effects on Biodegradation

Despite the general reliability of aerobic biodegradation in reducing PVI, several environmental factors can hinder this process. The most significant factor is the availability of O_2, which is a necessary electron acceptor and enzyme reactant in the aerobic biodegradation of PHCs. Roggemans et al. (2001) showed oxygen concentrations of 2% by volume to be supportive of aerobic biodegradation. Some state regulations/guidance documents indicate that O_2 levels only need to be greater than 2%–4% by volume to support aerobic biodegradation.

Some factors that may hinder the recharge of O_2 in the vadose zone are soils with high moisture content; soils with high organic content at shallow depth; soils with low permeability; large tightly sealed/intact building foundations; and the presence of high PHC concentrations, such as near LNAPL sources, that consume O_2 from biodegradation itself. In the absence of O_2, anaerobic microorganisms can use other electron acceptors (e.g., nitrate NO_3^-, manganese Mn^{4+}, iron Fe^{3+}, sulfate SO_4^{2-}, and methane CH_4) to support PHC biodegradation. Anaerobic biodegradation of PHCs is typically much slower than aerobic biodegradation, and the rates of biodegradation can vary substantially depending on the amount of O_2 available.

Other factors that can potentially limit the biodegradation of PHCs include low moisture content, nutrient availability, temperature, and heavy metals. In the vadose zone, sufficient moisture and nutrients usually are present to support microbial PHC biodegradation. In more extreme circumstances (such as arid environments), insufficient moisture can potentially limit PHC biodegradation even when sufficient O_2 is available. In general, the rates of biological processes decrease with decreasing temperature. Cold climates, however, do not preclude the potential for biodegradation because some specific PHC-consuming microorganisms thrive in temperatures ranging from 20ºC to 0ºC (Margesin and Schinner 2001). Similarly, heavy metal chemicals can be toxic to PHC-degrading bacteria and can decrease PHC degradation rates (Babich and Stotzky 1985). Many microorganisms, however, have the capability to resist the toxic effects of heavy metals and have high activity in environments affected by these common inorganic chemicals. Heavy metals can be considered as the RCRA metals (arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver).

2.2.7. Subsurface Considerations

2.2.7.1. Capillary Fringe

The capillary fringe interface separates the vadose zone and groundwater. While above the water table, the water content of the capillary fringe is still significantly higher than in the overlying vadose-zone soils. This results in lower air content and effective diffusion coefficient within the capillary fringe, which can significantly reduce upward diffusion flux. As a result, attenuation across the capillary fringe can be substantial, especially if the capillary fringe water is due to infiltrating precipitation or surface waters and not contaminated groundwater. This may not be the case when the groundwater table drops and leaves contaminated water in the soil pores.

Because of the attenuation of VFC concentrations across the capillary fringe, and because soil vapor conditions do not reflect a purely mixed solution, soil vapor concentrations are typically lower than the equilibrium concentration predicted by Henry's Law (when the source of the VFCs in soil vapor is groundwater COCs). The capillary fringe effect will be more significant in fine-grained soils, with thicker capillary fringes and lower effective diffusion coefficients, than in coarse-grained soils. The contribution of the capillary fringe to attenuation of VFC concentrations over the soil profile can be assessed by groundwater and soil vapor concentration data, and/or by modeling, e.g., the Johnson and Ettinger model (J&E model) (California DTSC 2024; USEPA 2017b).

2.2.7.2. Lateral Screening and Vertical Separation Distances

The upward migration or diffusion of VFCs from subsurface sources can potentially impact overlying or nearby buildings. The definition of *nearby* for site-screening purposes is often based on a lateral distance beyond the vapor source (e.g., the edge of a groundwater plume), sometimes called the lateral inclusion distance (Figure 2-7). In some cases, a vertical screening or separation distance is used for site screening, particularly for PVI (see Section 5.3.2.1 Application of Distance-Based Screening), above which sources are considered unlikely to result in sufficient diffusion flux for the VI pathway to be of concern.

The USEPA recommended a lateral inclusion zone distance of 100 feet between the nearest edge of the building foundation and the outermost and uppermost edge of the VFC source (USEPA 2002c) as defined in Section 5.3.2. For states that have published guidance on lateral inclusion distances (approximately 26 states as of 2023) most adopt the same criterion for VFCs (Eklund et al. 2024, which was shown to be an adequate screening distance in most cases based on empirical (Folkes et al. 2007) and modeling studies (Lowell and Eklund 2004). The USEPA final guidance (USEPA 2015c) also suggests using an initial screening distance of 100 feet (laterally and vertically) but recommends evaluating and potentially refining the exclusion distance as site-specific data and information are collected.

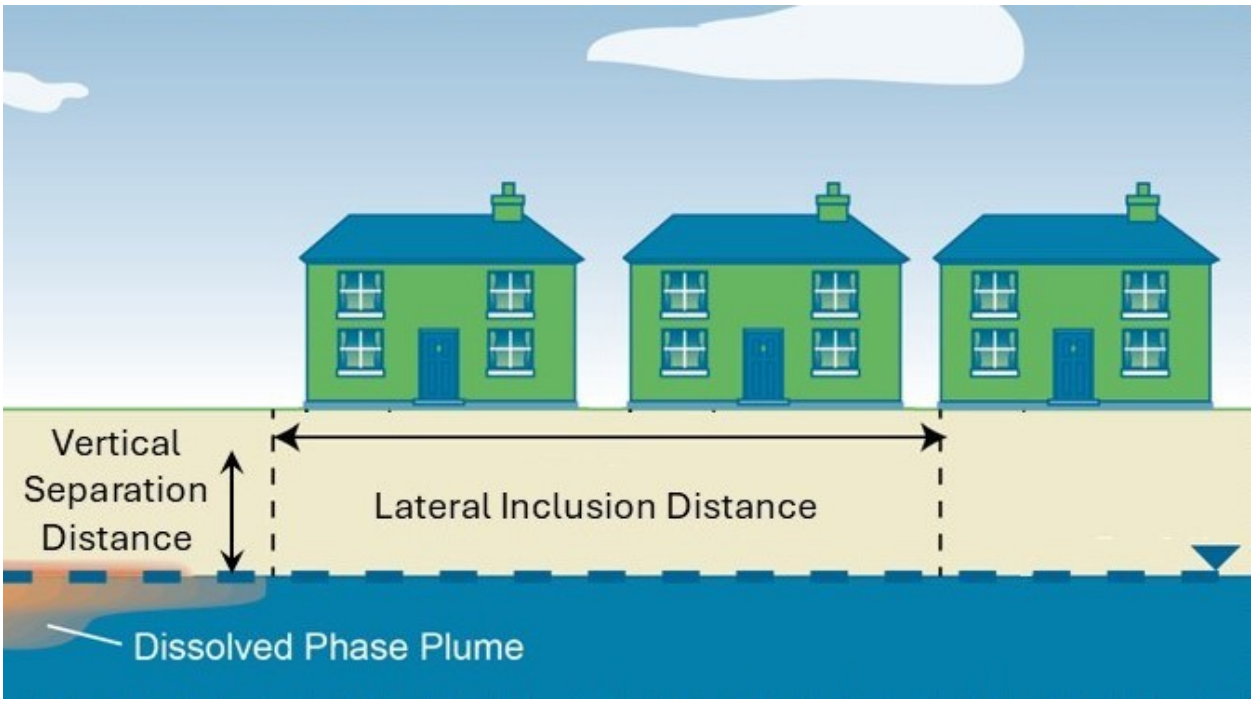


Figure 2-7. Lateral screening and vertical separation distances.

Yao et al. (2015) evaluated the effects of impervious soil covers and geologic layering on the lateral extent of VFC diffusion using three-dimensional and analytical models, concluding that the three key factors that contributed to lateral migration distance were source strength, source depth, and presence or lack of an impervious surface cover. The 100-foot lateral distance criterion was found to be sufficient and usually conservative, except in cases where the source concentration was considerably high, the source was deep, and an impervious cover was present over a substantial portion of the 100- foot zone.

Some states (approximately 28 and DC as of 2023, see Eklund et al. 2024) have adopted a shorter lateral inclusion distance of 30 feet for PHCs because aerobic biodegradation is likely to limit the extent of petroleum chemical migration, as discussed in Section 2.2.6, above. Similarly, USEPA (2015) has also recommended the use of shorter vertical separation distances (between the vapor source and the

building) to screen sites for the potential for PVI, as discussed in Section 5.3.2.1 Application of Distance-Based Screening. A 30-ft lateral exclusion distance, as well as a shorter vertical separation distance, may be applicable to other aerobically degradable VFCs. The overseeing regulatory agency should be consulted before application of any lateral or vertical inclusion distances that are not included in applicable guidance or regulations.

2.2.7.3. Biotic and Abiotic Considerations

Within the vadose zone, water and air coexist in the pore spaces of soil or rock, influencing both biotic and abiotic components.

Abiotic components are the nonliving physical and chemical elements in the vadose zone. These include soil particles, minerals, air, water, and factors like temperature, pH, and moisture content. Abiotic factors shape the physical environment where biotic components live and influence biological activity.

Biotic components refer to the living organisms in the vadose zone. These include microorganisms like bacteria and fungi, as well as plant roots and soil fauna such as insects or earthworms. Biotic elements interact with their environment through processes like decomposition, nutrient cycling, and organic matter production.

The interaction between these components is crucial. For example, the availability of water (an abiotic factor) affects the survival and activity of microorganisms (biotic), while microbial activity can alter soil chemistry, influencing abiotic conditions. In the vadose zone, both biotic and abiotic factors play significant roles in the migration of chemicals:

- Abiotic Factors:
    - **Soil Composition:** The type of soil (e.g., sandy or clayey) affects the movement of vapors. Sandy soils, for instance, allow easier vapor migration due to larger pore spaces.
    - **Moisture Content**: Water in the vadose zone can act as a barrier, slowing down or blocking vapor movement. Dry conditions can enhance vapor migration.
    - **Temperature and Pressure:** Variations in temperature and barometric pressure can influence the rate and direction of vapor movement.
- Biotic Factors:
    - **Microbial Activity:** Microorganisms in the vadose zone can degrade some chemicals by reducing the concentration of harmful vapors. This process, known as bioattenuation, is a natural mitigation mechanism.
    - **Plant Roots:** Roots can alter soil structure and moisture content, indirectly affecting vapor migration pathways.

The interplay between these factors determines the extent and impact of VI. For example, high microbial activity in moist soils might reduce VFC levels, while dry, sandy soils with minimal microbial presence could facilitate faster vapor migration.

2.2.8. Clean Water Lenses

In cases where groundwater is the sole subsurface source of vapors, source strength is influenced by the vertical distribution of COC concentrations in the upper portion of the water table. A layer of clean water from recharge may accumulate above a VFC plume through infiltrating precipitation, irrigation, or clean water sources such as storm-water retention ponds or other hydrologic features. This layer is often referred to as a *clean water lens* or *freshwater lens* (Fitzpatrick and Fitzgerald 2002; McAlary et al. 2010).

The thickness of a clean water lens often grows with increasing distance from the point of the release, also referred to as a *diving plume* (API 2006). In cases where a clean water lens is present and VFCs are not within the uppermost groundwater table, vapor transport will be impeded due to the slower diffusion of volatile chemicals in water than soil vapor (USEPA 2015c); thus, a clean water lens can act as an effective vapor barrier, inhibiting partitioning of VFCs from the water table sufficiently to prevent or minimize the potential for VI by this pathway, as shown in Figure 2-8. This condition may not develop if water-table fluctuations are large, which would result in vertical mixing of VFCs across the upper water-saturated zone and/or in the vadose zone.

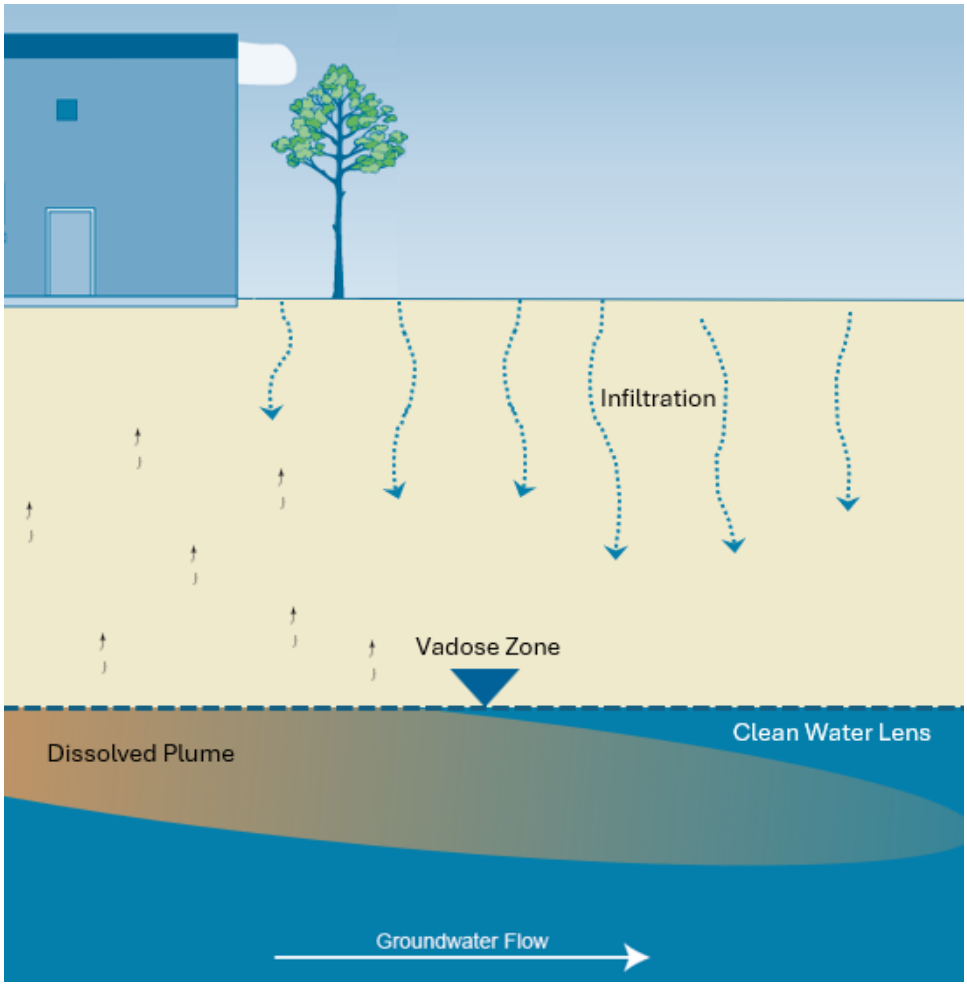


Figure 2-8. Clean water lens.

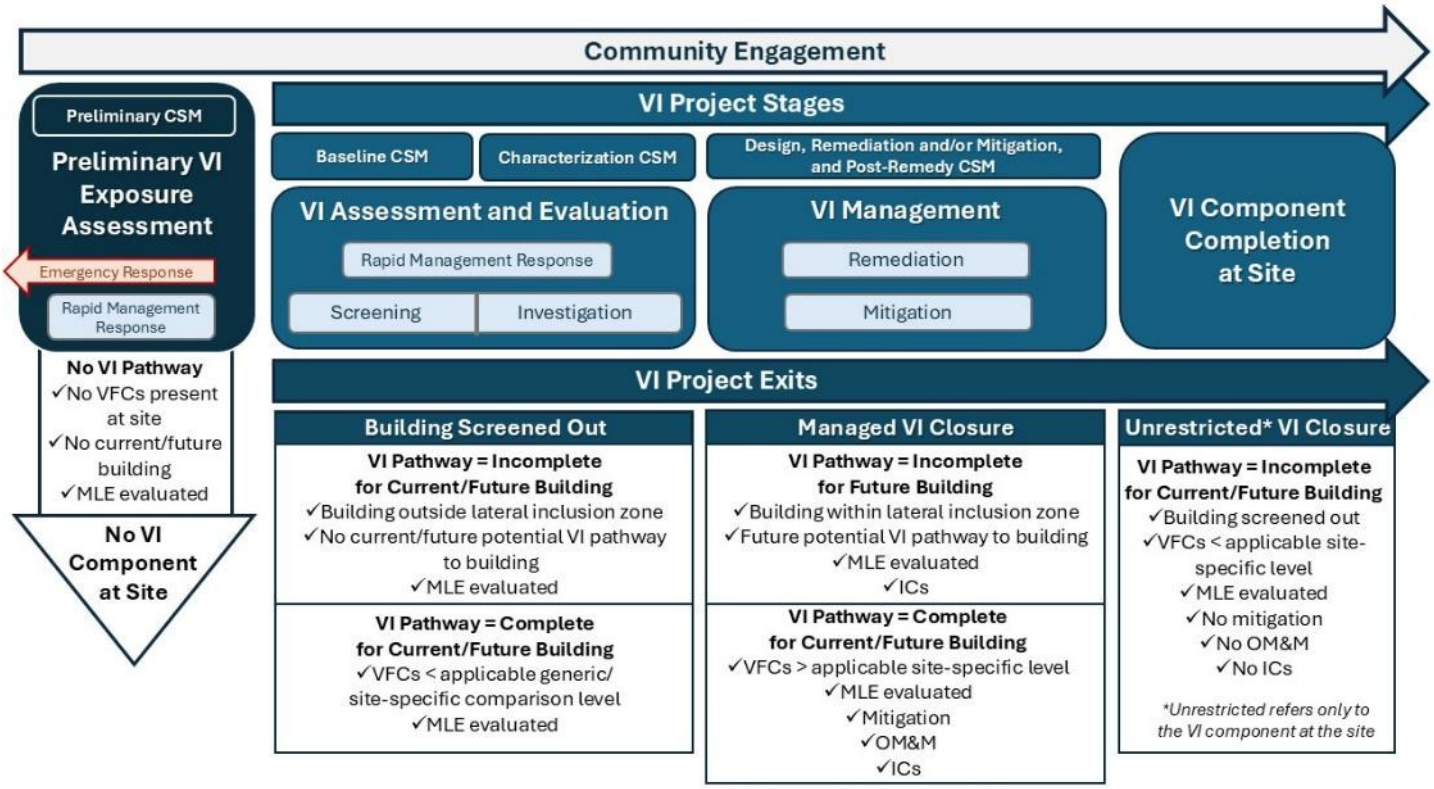
2.2.9. Emerging Vapor-Forming Chemicals

Contaminants of emerging concern are substances or chemicals that currently are not regulated but concerns exist about their potential for adverse human health and ecological impact. Emerging contaminants may include VFCs. Most recently, at the time of the publication of this guidance, per- and polyfluoroalkyl substances—known as PFAS—have emerged as chemicals that have a potential for adverse human health and ecological impact but for which little to no scientific data exists. For more information, please see the Vapor-forming Per- and Polyfluoroalkyl Substances (PFAS) Fact Sheet.

2.3. Vapor Intrusion Pathway Assessment Process

The VI pathway assessment process often begins with observations made during other assessments or investigations, such as Phase II environmental site assessments (ESAs), that indicate a potential for current or future VI. The first step is typically site screening, to determine whether further evaluation for VI risk is warranted, followed by investigations to evaluate the potential for VI risk, if necessary. The following sections provide a process flow chart for VI assessment, followed by high-level descriptions of the different components of the process. More detailed information is found in other chapters of this guidance document.

A consistent approach to VI that fits the applicable regulatory framework, VFC, and type of site is critical for confident decision-making that protects human health, such as the approach shown in Figure 2-9. This is an iterative process, beginning with a preliminary exposure assessment and potentially emergency or rapid response measures, if warranted. This may be followed by more initial and refined screening (based on additional available information if needed) and development of a baseline CSM. If screening indicates that further evaluation is warranted, this is followed by investigations to fill data gaps and further refinement of the CSM, leading either to a determination that the site can be screened out or that site management for VI (such as vapor controls, long-term monitoring, and ICs) is warranted. In addition, community engagement is a critical component of the process that should be considered throughout the VI project stages.



Notes: CSM = conceptual site model; IC = institutional control; MLE = multiple lines of evidence; OM&M = operation, maintenance, and monitoring; VFC = vapor-forming chemical; VI = vapor intrusion.

Figure 2-9. Vapor intrusion pathway assessment process.

Iterations in the screening and investigation phases may be warranted, depending on the need for additional information for decision-making purposes.

The following subsections introduce general information that will be discussed in more depth in subsequent chapters.

2.3.1. Preliminary Exposure Assessment, Vapor Intrusion Assessment, and Evaluation

To determine that the VI pathway is an exposure pathway, a vapor source, migration route, and receptor must all be identified. Specifically, the VI assessment entails the identification of all known or suspected vapor sources of COCs, consideration of the VFC migration routes including an evaluation of methods and manner of intrusion, and identification of those likely to be affected by the VFCs (receptors).

The physical source of the COCs should be determined. Identification of the initial or primary sources (e.g., a leaking tank or a surface spill) or secondary sources (e.g., contaminated soil vapor, soil, or groundwater) may assist in the VI investigation. Factors to consider when identifying likely sources include the following:

- Product type, chemical composition, and source location of COCs
- Contaminated media (groundwater, soil vapor, soil)
- Chemicals of interest present in each medium
- Distribution and concentrations of VFCs in each medium

The movement of VFCs from the source to the receptor, as described in **Section 2.1.3**, is a complicated process in the VI pathway and consists of multiple transport mechanisms (diffusion, advection) and can be enhanced or impeded both in the subsurface and within the targeted building.

Receptors, as they relate to the assessment of VI, may include any occupant of a building or the building that is or has the potential to be adversely affected by the migration of VFCs. When evaluating VI via inhalation pathway, receptors are typically people who may be exposed to the site-related VFCs. Typical receptors include adults and children exposed in a residential setting, adults exposed in an occupational (i.e., work) environment, and adults and children exposed in a nonresidential setting. Other site-specific exposure scenarios (e.g., schools, day-care facilities) may be identified.

Identification of possible receptors can be determined using the location of the site being assessed, locality of the facility data, land use data, and demographics. Specific considerations in evaluating receptors might include the following:

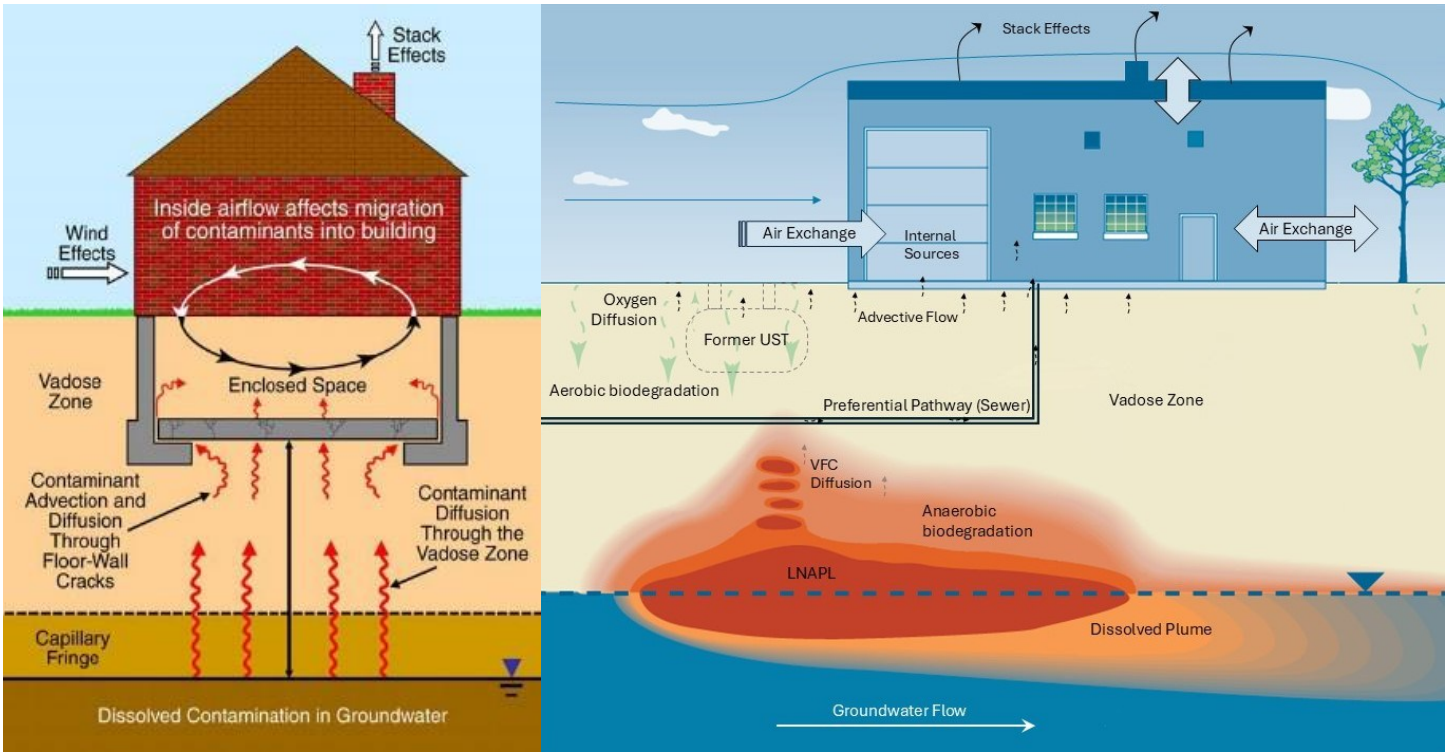
- Future site use and surrounding area use
- Buried utility conduits (e.g., storm sewer, sanitary sewer, subsurface drains, water supply, electrical, cable) in the area
- Zoning criteria (commercial, industrial, residential, and mixed-use) and zoning exceptions (e.g., commercial zones that allow residential, multifamily residential, second-story residential; some industrial zones allow a caretaker to live on the site; other commercial zones allow unique uses, such as day-care facilities)
- Land use constraints
- Site vicinity and conditional uses typically allowed
- Regulatory authority and state guidance

2.3.1.1. Conceptual Site Model

CSMs are simplified versions of complex systems and are "an important tool for organizing information about the current state of knowledge and understanding of the problem" (USEPA 2006c, 16). CSMs can come in several forms to meet the needs of the practitioner. For example, CSMs created to describe contaminated sites to nontechnical stakeholders are typically represented in a simplified diagram.

CSMs commonly break down complex systems into their basic components and then describe the relationships among these components. The graphical model typically uses a simple indication, such as arrows, to show how COCs move from the source, through the environmental media, and toward the receptor.

VI occurs when vapors from contaminated groundwater or other subsurface sources migrate upward through vadose-zone soils and into overlying buildings. The concern is when the vapors accumulate to concentrations above screening levels set by regulatory agencies. The VI CSM provides a general overview of the VI pathway, including the locations and types of vapor sources, subsurface vapor transport mechanisms, foundation and other building conditions affecting the rate of vapor entry, and receptors that could be impacted by VI. In addition to the above, a CSM for PVI incorporates biodegradation. The VI CSM helps the practitioner evaluate the potential for a complete VI pathway, identify data gaps, and communicate findings and conclusions to other stakeholders. The CSM also plays a key role if a site moves to mitigation as the CSM will help to determine the most effective type of mitigation for a particular site. **Figure 2-10** depicts a general CSM for the VI pathway process. A CSM is a summary of site-specific conditions and describes the relationship among VFC sources, affected media, migration pathways, and potential receptors. Types of CSMs, components of a CSM, and considerations during development of the CSM are discussed in greater detail in **Chapter 4: Conceptual Site Model**, **Chapter 8: Data Evaluation and Vapor Intrusion Risk Assessment**, and **Chapter 10: Vapor Intrusion Mitigation**.



Note: UST = underground storage tank, VFC = vapor-forming chemical.

Figure 2-10. General conceptual site models for the vapor intrusion pathway.

2.3.1.2. Site Screening

Site screening (**Chapter 5: Site Screening**) is undertaken at sites with VFCs in the subsurface to identify potential threats to human health associated with their migration from the subsurface to indoor air and subsequent inhalation. The purpose of site screening is to identify current and future buildings where more detailed VI site assessment is needed (i.e., site where additional actions are triggered) or can be ruled out because VI exposures are not a concern. Such determinations are based on a preliminary VI exposure assessment that documents the presence of VFCs in the subsurface and the potential for VI to occur because of a plausible linkage between the VFC source and a current or future building. This initial exposure assessment is considered by some regulatory agencies to constitute VI screening, while others consider the assessment to be an element of the VI screening process. The three possible outcomes of the preliminary VI exposure assessment are (1) site conditions warrant emergency or rapid response, (2) no further VI evaluation is necessary, or (3) a more detailed assessment and evaluation or mitigation or remediation must be undertaken. VI could potentially occur because of the presence of a VFC source in the subsurface, current or future buildings (receptor), and plausible pathways for VFCs to migrate from the source to the receptor. Sites where a potential source-pathway-receptor linkage is identified are then evaluated for more detailed VI screening based on distance, concentration, or mass flux.

The VI screening process requires some amount of information needed to perform VI screening and will vary depending on the complexity of the VI CSM (potential sources, pathways, and receptors) and screening methods (e.g., distance-based, concentration-based, or mass-flux-based screening). It is therefore important to review the minimum data requirements of each screening method prior to implementing any steps of the VI screening process. See **Section 5.1.1 Screening Requirements** for more information.

Lastly, it is important to note that VI screening is intended to be a conservative approach, relying on conservative, default exposure assumptions meant to be protective of human health.

2.3.1.3. Investigation

The site investigation process (see **Chapter 6: Iterative Investigation Process**) further refines the nature and extent of impacts at a site to help answer the investigative questions being asked. Through the collection and analysis of data, the site investigation process attempts to describe some factors that are important for understanding site conditions, including but not limited to the following:

- Biodegradation influences
- Geologic and hydrogeologic characteristics
- Building characteristics
- Nature and extent of impacts
- Vapor source characteristics
- Spatial and temporal variability of vapor concentrations in and beneath buildings
- Conceptual site model (CSM)

2.3.1.3.1. Building Owners and Occupants

Most other media (e.g., soil, groundwater) and exposure pathways (e.g., contact with soil or groundwater) are assessed using exterior investigative tools to characterize and delineate COCs. While the actions to characterize and remediate contaminated groundwater, soil, or sediments may be apparent to the community, they typically are not invasive to the personal lives of individuals. VI, on the other hand, may

involve the collection of environmental samples inside or immediately below a building. Thus, the process of investigating the VI pathway often directly affects occupants, increasing the importance of community engagement throughout the entire VI pathway assessment process. See **Chapter 3:Community Engagement** for more information.

2.3.1.3.2. Sampling and Analytical Methods

Selected sampling and analytical methods should be based on those that best meet the investigation goals and data quality objectives (DQOs) defined during the project planning process. In general, sample methods can be defined as active or passive, with each having media-specific methodologies dependent on applicable screening levels, chemicals of potential concern (COPCs), detection limits and precision, sample duration, or applicable regulatory agency requirements or recommendations. Most laboratories report air data in µg/m^3 and parts per billion by volume (ppbv). These are not equivalent to µg/l or mg/l. Converting between units is a common source of error. See **Chapter 7: Sampling and Analysis**, **Chapter 8: Data Evaluation and Vapor Intrusion Risk Assessment**, and the **Units and Unit Conversions Fact Sheet** for additional information.

2.3.1.4. Data Evaluation and Vapor Intrusion Risk Assessment

Throughout the VI project life cycle, information, qualitative and quantitative data will be gathered and evaluated (**Chapter 8: Data Evaluation and Vapor Intrusion Risk Assessment**) to determine whether there is a complete exposure pathway for VFCs to migrate from the subsurface to indoor air for current and potential future exposure scenarios, and what the implications are if a complete or potentially complete VI pathway is identified. The process of evaluating whether there is a complete or potentially complete exposure pathway to subsurface chemicals volatilizing into indoor air (i.e., VI)—either in existing buildings or potential future buildings—typically starts with a preliminary screening to eliminate low-risk sites from further consideration. Sites that are not eliminated at this initial step are evaluated using more site-specific considerations to determine whether there would be a risk if the exposure pathway for VI were complete or potentially complete.

These evaluation methods can be used to make a sound, technically defensible determination as to whether or not the VI pathway is complete (or is incomplete and warrants no further investigation), evaluate the potential risk associated with pathways that are found to be complete, and inform decision-making about next steps, such as further investigation, remediation, or mitigation. Due to the complexities with evaluating risk from VI, the amount and type of information and data available for each site and/or building will vary.

It is important to note that during any part of the VI project life cycle, the potential for acute exposure of building occupants to contaminants from the VI pathway should be considered. See **Section 5.2.3 Evaluation of Emergency or Rapid Response** for more information.

2.3.2. Multiple Lines of Evidence

When evaluating complex relationships among groundwater, soil, soil vapor, and air, decisions cannot be made on any single, simple fact, procedure, or data point. Investigators must gather, evaluate, and weigh different types of data and information. Thus, multiple independent sources of information, often termed *lines of evidence (LOEs)*, must be evaluated to determine whether VI is occurring or likely to occur. Assessment of all available LOEs is recommended before drawing conclusions about the exposure risks.

When more than one LOE is used to draw conclusions about the condition of a site, the process is referred to as an MLE approach. It is up to the investigator to gather, evaluate, and weigh different types of data and information. Different, but not necessarily all, media can be sampled to evaluate MLE. Collecting MLE is particularly helpful because of the complex nature of the transport of vapors and the

inhalation exposure pathway, and because VFCs can be ubiquitous in indoor air from background sources.

See the **Multiple Lines of Evidence Fact Sheet** for a detailed discussion of the application of MLE.

2.3.3. Use of Mathematical Models

All models are simplifications of complex systems. In the simplest terms, modeling requires the input of certain site information into the model, which then mathematically evaluates that information and produces output describing the site. For VI, for example, the USEPA's VISL calculator or J&E model can be used to conservatively predict the potential for VI to indoor air for chlorinated solvents (e.g., tetrachloroethene [PCE, also called perchloroethene and tetrachloroethylene], trichloroethylene or trichloroethene [TCE], and vinyl chloride). For PVI modeling, computer models, such as BioVapor or PVI Screen can be used to predict the behavior and biodegradation of vapor-phase chemicals, such as benzene, in the environment. Using models can help to predict where VI vapors might (or might not) occur and, if they occur, in what quantity. Models may also be used to predict the maximum extent of VI. Regulators and other environmental professionals can use model results to focus VI investigations where resources are needed most and to provide boundaries outside of which little or no sampling is required. Models are updated as more VI information becomes available.

VI models may be useful for sites that require further assessment based on the screening and application of the screening distances described in **Chapter 5: Site Screening**. The complexity of modeling applications can vary greatly depending on the objectives of the modeling and availability of project-specific information. The acceptance of VI models and the results is variable among local, state, and/or federal agencies. Where applicable, models can be used as MLE.

Prior to conducting any model simulations, the purpose and objectives of the modeling should be clearly understood and defined. The modeling objectives and purpose play a role in model selection. The objectives can also influence selection of parameter values and can help to determine the level of detail and accuracy required in the model simulations. See **Chapter 9: Modeling** for additional discussion on this topic.

2.4. Vapor Intrusion Mitigation

The VI investigation may indicate that concentrations of VFCs in indoor air exceed mitigation action levels or are likely to exceed screening levels in future buildings and that actions should be taken to reduce the amount of VI into a building, reduce the potential for future VI into a building and/or reduce exposure to impacts present in indoor air that occurred as a result of VI. VI can be managed by environmental remediation, ICs, building mitigation, or any combination of these approaches. *Remediation* in this guidance refers to actions that reduce the residual mass found in the environmental medium (e.g., groundwater or soil) that is acting as the source of vapors. *Mitigation*, on the other hand, refers to actions that reduce exposure from the VI through the VI into indoor air pathway.

When the VI investigation indicates that an action is needed, a remedy or combination of remedies should be selected, implemented, operated, maintained, and monitored to properly respond to VI or potential VI. This may include traditional remedial technologies applied to the source that may be sufficient to mitigate VI for buildings located close to the source. Alternatively, ICs or building mitigation systems can mitigate the potential for VI either as part of the site management strategy or as an interim measure while longer-term remedies are being developed and implemented. The CSM should be used to help determine an effective site management strategy. Regardless of the management tools used, the CSM should be refined and the VI pathway reevaluated as conditions change or new information becomes available.

Mitigation and closure or other endpoints are summarized below and discussed in greater detail in Chapter 10: Vapor Intrusion Mitigation.

2.4.1. Emergency and Rapid Response

Rapid response is limited to scenarios where there may be an acute risk to human health from VI and does not include emergency situations (i.e., call 911 situations) where combustible, explosive, or oxygen-deficient conditions may exist inside a building and should be addressed as emergency response conditions before beginning or continuing a VI investigation (see Section 5.2.3 Evaluation of Emergency or Rapid Response) If these conditions are believed to be present, ***immediately*** **evacuate the building** and contact first responders.

Rapid response is an interim VI mitigation approach that may be appropriate, under certain conditions, prior to implementing a long-term mitigation strategy for an occupied room or building. For the purposes of this document, a rapid response is one that could be easily implemented and verified on a timescale of days to weeks and operated on a short-term basis while more complex mitigation strategies are implemented. A long-term mitigation strategy will take longer to design, implement, and verify and is intended to operate either as part of the long-term site strategy or until the remedial objectives are met. Note that some technologies or mitigation methods characterized in this document as rapid response may also be suitable as long-term mitigation strategies.

For cases where VFCs are detected in indoor air at concentrations exceeding short-term exposure criteria, a rapid response is typically warranted. Rapid response actions may also include administrative controls, such as evacuating and eliminating occupant access to the building or portions of the building, or engineering controls (ECs) that reduce chemical vapor exposure through building ventilation, indoor air treatment, or physically preventing vapor entry into the building (e.g., crack sealing). For more information, see the Rapid Response and Ventilation for Vapor Intrusion Mitigation Fact Sheet.

2.4.2. Active Mitigation Technologies

Active mitigation technologies are typically applied below the building slab. The most common approaches involve extraction of vapors from the subsurface materials (e.g., soil or gravel) immediately below the building and discharging them outside the building via the use of mechanical means such as an inline fan or blower. Sub-slab depressurization (SSD) systems and sub-slab ventilation (SSV) systems are the most commonly installed types of active mitigation. Other approaches detailed in the Active Vapor Intrusion Mitigation Systems Fact Sheet include sub-membrane depressurization (SMD) and crawl-space ventilation (CSV). Important considerations for active mitigation technologies are properly designing and installing the system, post-installation verification, and ongoing performance monitoring. In addition, plans for future potential shut down and decommissioning should be considered during the planning phase.

2.4.3. Passive Mitigation Technologies

Passive mitigation technologies are primarily intended to modify the VI pathway without the use of electrical or mechanical means and commonly involve creating a barrier to vapor migration through the slab, such as barriers placed immediately below slabs (new construction), sealing of cracks and other openings in slabs, and surface coatings.

Common passive mitigation barrier systems are detailed in the Passive Vapor Intrusion Mitigation Systems Fact Sheet and include asphalt latex membranes, thermoplastic membranes, composite membranes, and epoxy floor coatings. Other passive mitigation measures detailed in the Passive Vapor Intrusion Mitigation Systems Fact Sheet include passive venting systems, such as passive sub-slab

venting and aerated floor systems, and building design specifications, such as raised foundations or vented garages.

2.4.4. Remediation and Institutional Controls

In some instances, environmental remediation technologies can serve a secondary purpose as VI mitigation. Remedial technologies detailed in the **Vapor Intrusion Remediation and Institutional Controls Fact Sheet** include soil vapor extraction (SVE) and multiphase extraction (MPE), which includes extraction and treatment of both groundwater and soil vapors.

For site remediation technologies to also serve as VI mitigation systems (VIMS), they must be able to reduce concentrations of the VFCs in indoor air below the applicable regulatory levels. Remediation technologies that can potentially serve that purpose, depending on site and building-specific conditions, include SVE and MPE.

ICs are a form of land use controls (LUCs) that provide protection from exposure to site-related VFCs through administrative or legal restrictions on site use, such as restrictions on residential use, schools, and/or day-care centers. ICs are primarily government controls, proprietary controls (e.g., deed restrictions), enforcement or permit mechanisms, and informational devices. LUCs can also require the use of ECs, such as physical barriers or the installation of mitigation systems in new buildings.

2.4.5. Vapor Intrusion Assessment Exit Points and Closure

A key concept throughout the process of designing, implementing, and operating a mitigation strategy is also evaluating options for assessing and implementing exit strategies. For example, the source of VFC vapors may eventually be remediated or attenuate to the extent that mitigation is no longer necessary. The selection of an appropriate exit strategy and whether remaining VFC sources still present an unacceptable VI risk will depend on site-specific conditions and should be approached as a process, rather than as an event (see **Chapter 11:Vapor Intrusion Component Determination, Exit Points, and Closure**).

This portion of the page left blank intentionally. Next chapter starts on the following page.

CHAPTER 3: COMMUNITY ENGAGEMENT

3.1. Introduction

It is important to engage the public at environmental contamination sites, but at VI sites, it is essential to engage the people who own, live, work or study in, or otherwise occupy impacted buildings. Their cooperation, not just permission, makes it possible to investigate, remediate, mitigate, and monitor properties contaminated or potentially contaminated with VFCs. The practitioner may be asking them to agree to allow intrusive or disruptive activities such as coordinating multiple entries, drilling holes through their floors, attaching fans and/or piping to their buildings, or rearranging rooms to accommodate investigatory/mitigatory activities. A successful outcome in which good decisions are made and stakeholders cooperate in the process requires building and maintaining trust.

Community engagement, risk communication and *public outreach* are among the many terms to describe communication between environmental response teams and stakeholders. This document uses the term community engagement for consistency.

The environmental team consists of many individuals including technical experts, project managers, field geologists, engineers, mitigation specialists, and installers. Everyone on the team may interact with the public at some point and should be trained in either basic risk communication skills or have contact info for team members who can answer questions. This document uses the term *practitioner* to describe an individual dedicated to providing community engagement leadership for vapor intrusion sites.

For this document, *stakeholders* is used to describe people who own, live, work or study in or otherwise occupy impacted buildings. **Section 3.2.1** provides more specifics.

Before the first announcement or knock on a door, the environmental team should develop and implement a community engagement plan that recognizes the unique character of each community and the form of planned investigation or mitigation, among other items. Having a plan from the onset will ensure being established as a credible source of information as work at the site progresses. While the contents and logistics of a community engagement plan for a VI issue are listed in the callout box below, they are integrally related and will need to be developed together. Above all, consider that there is no substitute for listening to the concerns of stakeholders at a site, and plans may need to be altered in response to their concerns.

The sections in this chapter focus on community engagement needs specific to VI. ITRC's Risk Communication Toolkit (ITRC 2020b) provides valuable information on general community engagement needs for all environmental response sites.

This Community Engagement chapter is organized sequentially by topics a practitioner can expect to arise as work at a VI site progresses.

- Section 3.2 Community Engagement Plan and Approaching Stakeholders for Investigation contains the basics for developing an initial site plan and modifications that may need to be considered in the future.
- Section 3.3 Stakeholders' Concerns summarizes common stakeholder concerns. Tables presented later in the chapter provide details on general stakeholder concerns and concerns specific to investigation and mitigation if a project progresses to those phases.
- Section 3.4 Explanation of Complex Topics covers vapor-specific science topics that are important to communicate to stakeholders in a way that they can understand.
- Sections 3.5 Mitigation (Remedy Needed) and 3.6 Long-Term Stewardship Best Practices recommend best community engagement practices if a response is required.

- Section 3.7 Development reviews global topics that should be considered at the outset if they apply to a site.

3.2. Community Engagement Plan and Approaching Stakeholders for Investigation

An effective community engagement plan will recognize not only the characteristics of a community involved but also the unique issues with VI. Unlike any other contaminant pathway, VI merits effective education of the affected community regarding the risk of soil vapor migrating from the subsurface as well as background sources typically found in buildings because people can be directly exposed in their home or workplace. Having a community engagement plan from project onset is the best way to become a trusted source of information for the community as the site progresses.

Community engagement plans must necessarily be tailored to individual sites, but typical components are listed below:

1. **Objectives:** Define clear, specific goals that you aim to achieve through community engagement.
2. **Stakeholder Identification:** Identify and prioritize the key groups and individuals who have a stake in your project.
3. **Methods and Tools:** Decide on the approaches and tools you'll use to engage the community. This might include surveys, public meetings, social media outreach, workshops, or community events.
4. **Communication Plan:** Develop a strategy for communicating with stakeholders, including how often and through what channels you'll share updates.
5. **Timeline:** Create a detailed timeline that outlines when different engagement activities will take place.
6. **Resources:** Identify the resources you'll need, including budget, staff, and any other necessary tools or materials.
7. **Evaluation:** Plan for how you'll measure the success of your engagement efforts. This could involve setting metrics for participation, feedback quality, and overall impact.
8. **Feedback Loop:** Establish a process for collecting and responding to community feedback throughout the engagement process.

Many examples of general communication templates exist including **ITRC's Risk Communication Toolkit**. This document focuses on how to tailor the plan for vapor intrusion sites.

3.2.1. Identify Stakeholders

It is critical to identify all stakeholders involved or potentially involved at a VI site. In addition to property owners (including their leaseholders and tenants) and other community members, stakeholders that should be kept informed of site activities are included in Table 3-1.

It is always best to be as inclusive as possible and reach out to all potential stakeholders through various means of communication (see Section 3.2.5 Property and Building Access). The practitioner should prepare for varying levels of technical understanding to exist within the community and be prepared to communicate at all levels. It is unrealistic to expect outreach efforts will reach all stakeholders. Despite best efforts, some in the community may assert that they were left out of a communications effort or process, and there should be a plan to address these concerns, if raised.

While members of tribes and native villages are stakeholders with concerns similar to those of other stakeholders, their governments "are sovereign entities that have established government-to-government relationships with federal, state, and local governments—relationships that must be recognized in the decision-making process." See Section 13.2, "Specific Tribal Stakeholder Concerns," of ITRC's September, 2023 PFAS Technical and Regulatory Guidance Document for more information (ITRC 2023).

3.2.2. Role of Risk Perception

According to ITRC's Risk Communication Toolkit, risk perception involves the influence of subjective factors on how risks are understood and valued. Stakeholders' risk perception regarding VI will depend on their knowledge, personal experience, and feelings as well as wider cultural and social factors. Risk communicators should understand that stakeholders' risk perception for VI will be influenced by the following factors:

- The difference between voluntary exposure (e.g., use of consumer products containing chemicals, whether aware of the hazards or not) and involuntary exposure (i.e., environmental contamination) due to the responsible party. See **Section 3.4.4.4** for further details.
- The difference between anthropogenic sources (e.g., discharge to the environment) vs. natural sources (e.g., radon).
- Impacted occupants have less control over minimizing their own exposure to contaminated air than other forms of contamination, such as contaminated groundwater. For example, alternative drinking water can be temporarily provided, whereas clean air is more difficult to achieve quickly.
- The constant evolution of science and regulatory requirements makes risk management strategies a moving target.
- VI data are more complex and harder to understand with regard to potential health impacts or possible illness. A typical investigation evaluates MLE, such as groundwater, soil vapor, sub-slab vapor, indoor air, outdoor air, preferential pathways, and meteorological factors (see **Section 2.4.2** and the **Multiple Lines of Evidence Fact Sheet** for more information).
- VI data are inherently more variable than other media.
- The familiarity of the occupants with VI science.

These factors make it important to let stakeholders know, prior to collecting the samples, how the sample results will be evaluated. For example, mitigation decisions may be made based on sub-slab vapor results; however, that does not mean that an unacceptable health risk has occurred. See **Chapter 8: Data Evaluation and Vapor Intrusion Risk Assessment** for more information on this topic.

People who are potentially impacted by VI vary in their scientific literacy. Listening to comments and questions can help the practitioner assess the scientific literacy of the community and address any misconceptions about environmental science. Government acronyms, scientific documents, and basic VI concepts such as soil vapor and advection may also be unfamiliar. Practitioners presenting information in an appropriate way provide context resulting in meaningful discussion of VI site specifics. Details on some of the complex topics specific to VI are discussed in **Section 3.4 Explanation of Complex Topics**.

3.2.3. Consistent Messaging

There are many general challenges in any environmental situation, including diversity of audience backgrounds, importance of establishing trust among the parties, and clearly communicating about the scientific and regulatory requirements of the intended action.

VI sites pose unique challenges to achieving meaningful and effective community engagement. Divergent information is often available from different sources about the potential severity and uncertainty associated with exposure and adverse health impacts that may result from exposure and the need for investigation or mitigation actions. For example, people will do their own research, which may result in conflicting information. Communicators must be prepared to explain the decisions made regardless of

the conflicting information. The risk communication challenge around health risks also lends itself to a scenario in which stakeholders, including potential responsible parties and applicable regulatory agencies, are not in agreement on the risk assessment and management strategy. Consistent messaging about uncertainties, as well as goals, from all stakeholders involved in the communication process is essential for effective risk communication and to best help those in need.

3.2.4. Community Engagement Tools

Many risk communication and public outreach tools are available for use, as well as a variety of methods to implement these tools. The means of communication (e.g., mailings, door-to-door outreach, public meeting/presentation, flyers) will likely be determined by the goals of the communication, the scope of the project (e.g., one or two buildings vs. an entire neighborhood or exterior investigation vs. indoor investigation), and consideration of stakeholder/audience needs. Public outreach material should be distributed in multiple modes to maximize audience reach and increase opportunity for engagement. Recommended modes of distribution include mailings, websites, local municipal health departments, public health professional offices, public libraries, social media, and information booths at community events. The community engagement plan should define the public outreach tools and modes of communication, as well as the roles and responsibilities of each stakeholder, including responsible parties and their consultants, regulators, state and local health departments, local governments, community advisory groups, etc. A well-organized plan will make it clear who is responsible for distributing materials and answering questions and also provide a routine means to discuss project progress to address issues as they arise. ITRC's Risk Communication Tool Kit Sections 2.3 -2.5 (ITRC 2020b) and ITRC PFAS Section 13.2 (ITRC 2023) contain valuable information on earning trust and credibility. If trust is an issue, practitioners should inform the public that technical resources, including independent assistance, are available through federal and state environmental or health agencies.

Although printed public education materials are effective at communicating information, additional efforts are often required to establish the level of trust necessary for an affected resident to grant access for investigation or to modify their building by installing a mitigation system. Techniques that include face-to-face communication, such as open-house meetings, focus groups, and door-to-door canvassing, are often more effective at addressing fears/irritation and building trust. Face-to-face communication provides the opportunity for questions and concerns to be answered in real time and also provides a basis to begin building trust and relationships that will be necessary for the ongoing investigation and mitigation efforts. Additionally, face-to-face communication provides an opportunity for practitioners to learn from the public and other impacted stakeholders. Making initial contact and achieving the opportunity for face-to-face communication is becoming increasingly difficult and will take extra effort.

The ITRC Risk Communication Toolkit (ITRC 2020b) Appendix H (ITRC 2020a) includes a Communication Methods Summary Table, which lists the pros and cons of the various methods. For VI sampling, door-to-door outreach will likely be needed on most sites to gain access for sampling. Considerations for door-to-door outreach are listed below:

- Visiting a home multiple times may be necessary to make contact, as well as to build needed trust. Consistency and persistence are key. With the advent of video doorbells, fewer people may be answering the door if they are not expecting someone. Advance notice is very important, if achievable.
- Knowledge of the community will help determine the best time of day to contact residents, occupants, managers, or owners. Some states have specific requirements for the number and timing of communication attempts.
- Dress in a manner appropriate for the community.

- Timing is important. It is essential to try to directly connect with occupants prior to a media announcement.
- Address cultural language barriers by making sure risk communicators are prepared to speak in languages spoken by the community or have an interpreter available during the visits. Presentation materials should also be developed in languages spoken by the community. See **Appendix B: Example Documents for Wisconsin** example mitigation fact sheet.
- Address technical barriers by speaking and developing presentation materials in plain language.
- Anticipate additional resources required (multiple visits, presentation materials in multiple languages, interpreters, etc.) when establishing schedules and preparing cost estimates.
- For security, teams of two may be recommended for door-to-door contact. More than two can be too many.

3.2.5. Property and Building Access

To conduct an investigation or subsequent response on private property, the practitioner needs the permission of the property owner or its representative. In most cases, this means obtaining a signature on a legal access agreement. A verbal agreement *may* be sufficient, depending on the local regulatory authority. Since such permission is essential to the investigation, the community engagement plan should lay out a strategy for obtaining legal access to maximize the number of signed agreements. See **Appendix B: Example Documents** for examples of access agreements.

Access agreements should be in plain language, and they should be designed to address the typical concerns summarized in the next section and the stakeholder concerns table. Obtaining a signature should not substitute for a conversational explanation of what the practitioner plans to do and what is expected of the property owner. If an owner is hesitant, the practitioner should be prepared to explain the benefits of the proposed activity.

At rental properties, in addition to obtaining legal access permission from the property owner, it is usually also necessary to obtain access permission from building occupants. Coordination with the occupant is commonly needed to perform the investigation or mitigation work. In some cases, an occupant-signed access agreement may also be needed, although verbal agreement may be sufficient.

At some rental properties, there is an additional challenge. The occupant, such as a residential tenant, may want sampling to occur, but it may be more difficult to contact and obtain the signed permission of the property owner. New York state's approach is typical: "If you are a tenant in a building in the…soil vapor intrusion area and would like to request sampling, contact your landlord/property owner to request that the property owner comply with the State's sampling requests" (NYDEC 2024, 1).

If the property owner ignores or rejects requests from tenants and/or regulators, practitioners should be prepared to make the case for cooperation. Most regulatory agencies either do not have the authority to require property owner permission, or they are reluctant to exercise it.

Once sampling is conducted, regulators should be prepared to ensure that the results are provided and explained to tenants, as well as property owners, in a timely fashion. In some states, such as Wisconsin, practitioners are required to notify property owners and occupants of sample results within a specific time frame after receipt.

In multi-unit buildings, the investigating team should have a clear idea which units it intends to sample *before* seeking permission. In some cases, they will focus on basements, garages, and ground-floor units. If sampling in those spaces shows exceedances of criteria, inside units on upper floors may need to be

sampled. Practitioners should be prepared to communicate the sampling strategy with all tenants, either proactively or following the investigation as applicable, to minimize concerns and the spread of misinformation. This also can apply to neighborhoods where some homes/properties are sampled, and others are not.

3.2.6. Nonresidential Buildings

In some respects, community engagement at nonresidential buildings may differ from residences. For instance, in addition to communicating with property owners and business owners, the community engagement plan should provide a roadmap for ensuring that other building occupants are aware of the potential risk and the plan for addressing it and to answer their questions before and after sampling and/or mitigation. It is important to coordinate with the business owner as to how/when to communicate with employees. It is also important to differentiate occasional guests or visitors from full-time employees. One approach would be to place nonthreatening signs at entry points, letting people know where they can learn more about the investigation.

Schools, day-care centers, places of worship, and community centers tend to require more preparation for community engagement than other buildings, largely because explanations need to be given to parents or guardians, who might not be present when their children are. People tend to be more concerned—often emotionally—about environmental exposures where younger children are involved. It may prove helpful to offer childcare to allow more parents to participate and so discussions of risk are out of earshot of young ears. On the other hand, it might be useful to communicate directly with high-school age students. Furthermore, though the discussions about these buildings are likely to focus on children, it is important to remember that there are full-time teachers and other staff present in these types of nonresidential buildings.

Be prepared for the scenario where children, or others, might be exposed to VFCs both at home and in school. People are likely to have questions about playgrounds, parks, and other outdoor common areas. The community engagement plan should contain suggestions for addressing outdoor risks while making clear that the VI pathway is an interior phenomenon.

3.2.7. Public Repositories

A common challenge in VI investigations is information sharing of environmental data with the community through the investigation and cleanup of contaminated sites. VI investigations typically involve collecting large data sets from multiple sources leading to inconsistencies in reporting and communication of this information. In recent decades, advancements in the computing environment have allowed many U.S. regulatory agencies to shift from the traditional public repository in the file room to a centralized location on a web-based data management system providing online access to the environmental data. This shift in public repository housing is improving efficiency in investigation and cleanup information sharing, such as: (1) case transparency, (2) documentation, (3) scheduling and reporting inconsistencies, and (4) earlier communication of sampling results. The availability of technical documents online makes it possible for members of affected communities to consult remotely with community-oriented experts. Use of an online data management system should be considered as part of the community outreach plan to meaningfully engage with all members within the community and other parties involved in the investigation and cleanup of a contaminated site.

Common/best practices for such repositories are listed below:

- Provide timely notification to the stakeholders when new documents are added.
- Search for mechanisms that make it easy to find documents, even where the exact name or address of the project is not known.

- Provide contact information for officials who can answer questions about the site and the documents.
- Follow local and state requirements regarding the redaction of personally identifiable information such as building addresses.
- Provide access to older documents, even if in scanned form.

Instructions on how to access such information is typically included in community engagement plans.

3.3. Stakeholders' Concerns

3.3.1. Health

Many stakeholders will likely be concerned about their health. These concerns often become hot button issues, at times driving the strategy that regulators will take in addressing the VI pathway. Public education and community outreach are crucial to how people react to a potential finding of VI.

Regulators and practitioners commonly encounter a series of questions from concerned occupants, such as the following:

- Is the air that our children breathe safe, not only in our houses but also outside and in our local school or day care?
- A health officer can provide bottled water for occupants to drink when potable water has been contaminated, but what can be done when contaminants from VI are found in the air of our buildings?
- Could this be the reason I have (or my relative has) [insert health issue, such as cancer]?

These concerns should be recognized immediately and addressed as information becomes available while the investigation proceeds. Sampling and analysis procedures should be done as quickly as possible but should follow proper procedures. In some communities, stakeholders may request indoor air sampling as part of the initial site screening. Near-real-time or real-time sampling techniques (e.g., trace atmospheric gas analyzer) that help identify sources and migration routes may be preferred by community stakeholders and should be considered in some instances. Stakeholders typically want to know the results of any tests involving their homes as soon as possible but will need the results interpreted to understand what the data mean for them. See **Appendix B: Example Documents** for documents used to report sampling results.

3.3.2. Other Initial Concerns

Although health will be a primary concern, practitioners and regulators will likely encounter many additional questions. **Table 3-1** summarizes common issues that various stakeholders are likely to have. This table is organized by various stakeholders to help determine which concerns practitioners and regulators may need to consider for their particular site. An explanation for each concern follows.

Table 3-1. Other concerns.

Stakeholder	Commun-ications	Operations	Property Value	Health and Safety	Cooperation/ Trust	Access/ Privacy	Property Damage/ Aesthetics	Windows/ Doors	Pets
Residential									
Homeowner	X		X	X	X	X	X	X	X
Landlord/ Manager/HOA	X	X	X		X	X	X		X
Renter	X			X	X	X	X	X	X
Non-Residential									
Property Owner	X		X	X	X		X		
Business Owner	X	X		X	X	X	X	X	
Employee	X	X		X	X				
Student/ Parent	X			X	X				
Patient	X			X	X			X	
Congregant	X			X					
Visitor	X			X					
Future Buildings									
Local Officials	X				X				
Developers	X	X	X		X		X		
Future Occupants	X			X	X				

The indications in this table are intended to be generalities. There will likely be situations in which stakeholders do not manifest the identified concerns, and there may be situations where concerns are not marked or are not included in this table. Listening to and addressing the concerns of all stakeholders is a key part of engaging the community. Here is an explanation of each column:

- **Communications:** All stakeholders will want to know *what* is being investigated or treated at the properties or buildings in question, and *why*.
- **Cooperation/Trust:** VI responses, more often than other environmental responses, usually require the cooperation of building occupants, owners, and even local officials. Since VI situations are caused by environmental contamination, typically from human activities (e.g., methane can be generated naturally), stakeholders with ongoing involvement with properties often start with an attitude of mistrust, even if the original party is not involved and subsequent owners or regulatory authorities are investigating legacy contamination. Gaining cooperation and trust are significantly more difficult when being investigated by the party responsible for the contamination.
- **Access/Privacy:** To conduct a VI response, regulators and/or responsible parties usually need to obtain permission from occupants, owners, or both. This can have impacts on scheduling and interruption of daily life. In addition to concerns about vapors intruding into their spaces, they may be uncomfortable having strangers in their buildings.
- **Health and Safety:** The people who might be exposed to VFCs are likely to be concerned about both the short-term and long-term impact of those exposures. People with children may show the most

concern, but other personal factors, such as preexisting health conditions, may influence attitudes. Building occupants typically have questions about the relationship between vapor exposure and a wide range of health conditions.

- **Costs:** In most cases parties responsible for contamination, developers, or insurance companies pay for the cost of investigation and the installation of mitigation systems, if required. Financial liability should be made clear to all impacted stakeholders from the outset. It should also be made clear who will be responsible for long-term OM&M of mitigation systems, including paying for electricity for the ongoing operation of the system, routine inspections and monitoring, replacement of system components at the end of their life cycle (such as a fan), and costs for telemetry if part of a system.
- **Operations:** In large buildings, people responsible for the business or maintenance may be concerned about the time and effort required for their participation in the environmental response or the disruption to normal business operations.
- **Property Value:** Property owners are usually concerned that contamination issues might drive down the value of their property. It is often helpful to point out that investigation and/or mitigation may actually raise their property values through identification of issues (i.e., investigation) and applying protections (i.e., mitigation).
- **Property Damage/Aesthetics:** People who live and work in buildings where VI responses are being conducted may worry that the installation of mitigation systems will damage their property or just look unsightly. They are likely to be concerned about any holes being drilled in their floors during both investigation and mitigation.
- **Window/Doors/HVAC:** Sampling may require that windows and doors be closed, or that HVAC systems be either on or off, for the period prior to and during sampling. For some building occupants, this may be an inconvenience.
- **Pets:** People conducting investigations or installing mitigation should be aware of common significant concerns by pet owners such as exposure to noise, accidental release, interactions with workers, and other stresses/threats to the pets.

3.3.3. Investigation and Mitigation Concerns

As the project commences and investigations and mitigation occur, people will also be concerned about other impacts on their lives. For example, at residential properties, residents may be concerned that environmental responders will track mud on carpets. At commercial properties, concerns may include interrupting the workday or discouraging business. At schools, officials may want to avoid any environmental work during school hours. The response team should make sure that building owners, managers, and occupants are aware of the incidental impacts of each of the mitigation technologies proposed for that building (e.g., noise, electricity, disruption). Table 3-2 shows how some impacts and concerns apply to investigation activities and mitigation options. In some cases, informed occupants can help response teams tailor their response to affected buildings. The leaders of the mitigation response team should make sure that the contractors performing the installation are aware and respectful of the concerns of building occupants, owners, and managers. It is often advisable to quickly resolve any issues (e.g., replacing a shrub or flowers in the garden that were damaged), rather than letting the issue escalate. That does not, however, mean conceding to false accusations (e.g., something was stolen).

Investigation activities can be disruptive and may permanently alter buildings. Owners and occupants need to be involved in both simple things like placement of indoor air sampling devices and more intrusive activities like placement of sub-slab vapor ports.

Table 3-2. Investigation and mitigation: impacts and concerns.

Activity	Scheduling, Invasiveness	Noise	Building Contents, Belongings	Cost	Permit	Long-Term Management and Institutional Controls	Property Damage (utility strike, aesthetics)	Property Value (increase or decrease)	Notification for Future Occupants
Investigation									
Interview and Floorplan Layout	X		X						
Sub-Slab Probe Installation	X	X	X		X		X		
Sampling	X		X					X	
Sample Port Removal	X		X				X		
Mitigation									
Active Mitigation (e.g., Sub-Slab Depressurization Systems)	X	X	X	X	X	X	X	X	X
Passive Venting	X		X		X	X	X	X	X
Air Purifying Units	X	X		X		X	X	X	X
Heating, Ventilation, and Air Conditioning	X	X		X		X	X	X	X
Sealing Floors	X		X	X*		X	X	X	X
Temporary Relocation	X		X	X		X	X	X	X
Soil Vapor Barrier/Liner	X	X	X	X	X	X	X	X	X

*Usually, the cost of sealing floors is low compared to other forms of mitigation, but there are exceptions.

Similarly, owners, tenants, and other parties (including contractors and architects for new buildings) often have strong opinions about the aesthetic effects and inconvenience experienced with the location of mitigation system components, including fans, pipe runs, and vent stacks. Stakeholders should be engaged, and their considerations incorporated into the system design as early as practical.

Stakeholder Engagement: To ensure that stakeholder concerns and requirements are addressed early in the design process, the building owner, tenant, and other parties in the building should be provided with information regarding the mitigation system installation activities. See **Chapter 10: Vapor Intrusion Mitigation**, **Appendix B: Example Documents**, and the **Considerations for Design and Implementation of Mitigation Approaches Fact Sheet** for more information. Common items may include the following:

- Basic description of mitigation system (components, operation, etc.) To be installed
- Photos of typical system components to be expected
- Length of time for system installation and startup
- Any restrictions to access to or use of portions of their property during system installation
- Potential noise level from construction activities that may be expected with system installation (if anticipated to be disruptive to the building occupants)
- Other building activities that may need to be completed for system installation to be possible (e.g., a furnace needs to be raised to access the basement floor, or a staircase needs to be fixed so that the basement can be accessed safely by the workers); these activities may be part of the installation activities completed by the responsible party
- Contact information if issues or questions arise during the mitigation system installation

Communication with the property owners on their expectation of the design, if any, early in the design process will help to avoid problems during installation and operation. Homeowners should be made aware of the need for and importance of ensuring the proper functioning of the mitigation system. Items such as possible piping locations, blower locations, power use, how modification to the building may affect the performance of the mitigation system, and future system OM&M (incorporation of certain types of telemetry in the design may limit or reduce the need for frequent property visits) should be discussed in the design phase. Consideration should also be made to address the potential for noise issues for the building occupants, depending on the type and location of blowers planned for the design.

3.4. Explanation of Complex Topics

3.4.1. What Is Vapor Intrusion?

The people whose lives and properties are affected by VI responses generally know little about the science. This section is designed to highlight some of the questions that typically arise at VI response sites. Many people may know what *groundwater* or *water table* means, but few people know what *soil gas* or *soil vapor* is. They likely have never heard of the vadose zone. Before attempting community engagement, it is important to explain the basics of VI by providing the following information:

- Typically, lower air pressures inside buildings allow the entry of vapors from the subsurface through openings, even minuscule cracks or pore spaces in concrete slabs.
- If the soil vapor contains volatile chemicals, then this process can cause some of those vapors to enter the building.

- Although vapors will attenuate as they migrate into occupied spaces, they can still be present at levels that pose a health risk. The many different types of samples can lead to confusion since some indicate health risks and others are for delineation (see **Section 3.4.6 Sampling–Types and Uses of Samples**).
- The purpose of the VI investigation is to assess those risks to determine whether and how the risks can be managed to reduce exposures to safe/acceptable levels.

3.4.2. Explaining Risk Assessment

Most people are not familiar with the way risk is determined, and they are particularly unfamiliar with the complicated pathway that must be evaluated to determine VI risk. **Chapter 8: Data Evaluation and Vapor Intrusion Risk Assessment** gives a technical explanation for a risk assessment if the risk communicator needs further knowledge. ITRC's Risk Communication Toolkit (ITRC 2020b) is also a great resource.

3.4.2.1. Impact Depends upon Pathway Completion (Not Proximity)

It is best to explain this with a picture of the CSM relevant to the properties being evaluated (e.g., residence with or without a basement) (see **Chapter 4: Conceptual Site Model** for more information on CSMs). Practitioners will need to explain that the building's location in relation to the subsurface contamination will impact exposure risk and determine whether they are included in the evaluation since there needs to be a pathway for the contamination to get to a specific property or building. It should be explained that soil vapor moves radially (out in every direction from the source), whereas groundwater contamination moves with the direction of the groundwater flow, and soil vapor concentrations decrease with distance from the source. Additionally, soil vapor can also move through preferred pathways, such as piping.

Practitioners may encounter a series of questions from concerned occupants regarding the risk assessment such as the following:

- Am I at risk if I live or work here?
- What types of contaminants are in the air?
- How can I protect myself and my family?
- How did the contamination occur?
- Is the contamination spreading?
- How will I be informed about the progress of the investigation and results?
- Am I at risk from other pathways of exposure such as drinking water, gardening, etc.?

These concerns need to be thoughtfully addressed by the practitioner with responses that clearly explain the risk associated with the contamination and how it might impact the occupants' health, the specific chemicals present or potentially present at the site, ways to reduce exposure, information about the up-to-date CSM, the history of the contamination as it is understood, and a clear communication workflow, e.g., public meetings, informational sessions, and transparent reporting procedures for reference by the occupant.

It is important to provide balanced information. On the one hand, one should not dismiss health concerns. After all, that is why the investigation is happening. On the other hand, not everyone who is exposed suffers a health impact. That is, exposure may increase risk, but it does not necessarily cause disease.

3.4.2.2. Duration of Exposure

The practitioner should explain the difference between short-term (acute) and long-term (sub-chronic or chronic) exposures and how they would impact the receptors' health. It is important for stakeholders to understand that the risk levels for most contaminants are based on many years of exposure, (i.e., lifetime is calculated as 70 years).

If short-term exposure concerns are expected for contaminants present on a site, more frequent sampling may be warranted. In addition, communication will need to be timely and continual, providing the stakeholders with clear information on the risks associated with the contaminant. See **Section 2.4.1 Emergency and Rapid Response** for more information.

3.4.2.3. Tap Water Questions

The occupant(s) may be concerned with the risks of exposure to tap water through drinking, breathing VFCs (through showering, for example), eating garden vegetables, or skin contact. The practitioner should explain that water supplied to the home, unless on well water, is treated water from a utility and would not be sourced directly from the potentially contaminated groundwater. If the home does get potable water from a residential well, the drinking water pathway should be evaluated to determine whether alternative water sources are needed for bathing, cleaning (e.g., dishes, laundry), cooking, and/or drinking.

3.4.2.4. Types of Receptors

Risk assessments are conducted to promote the protection of vulnerable populations such as individuals with preexisting health conditions, the elderly, children, and women of childbearing age; these populations are also known as sensitive receptors. Sensitive receptors will want an explanation of what is incorporated into screening levels. It is important to explain that screening levels are often calculated and set based on the worst-case scenario and to be protective of the sensitive receptor groups mentioned above under these scenarios. This is when the concerns over short-term exposure, for example to TCE, can be presented or reiterated.

3.4.3. Building Type Affects Pathway

It is important for the practitioner to address concerns the occupant may have regarding their building type and how it can affect the VI pathway. Stakeholders may question the method of investigation (sample locations or type) used at their building as compared to what is being done in their neighbors' homes, (i.e., slab vs. crawl space, one story vs. two, etc.).

Since building ventilation can greatly impact VI into the building, occupants may have concerns about whether they should run their building's ventilation more or less to mitigate these risks. Residential properties may operate their HVAC intermittently depending on the daily changes in weather, whereas commercial properties may operate their HVAC on a more consistent basis or may only operate the HVAC during business hours. The operation and maintenance of the ventilation system can greatly impact its efficacy and thereby influence the factors of VI.

Identification and evaluation of the building type and the above factors that may cause concern for the occupant are typically determined during the process of completing a building survey, which may include an interview with the occupant and/or property owner. This step is crucial to understanding the specific scenarios affecting the potential for VI at each building. See **Appendix B: Example Documents** for sample building surveys.

3.4.4. Sources

VI can arise from a variety of sources, e.g., contaminated groundwater, contaminated soil, or via utility corridors running through contaminated properties, most of which are not familiar to affected stakeholders. In addition, some consumer products, such as E6000 craft glue or silver polish (which contain PCE) or brake cleaner or printer toner (which contain TCE), contain the same chemicals that are being investigated.

3.4.4.1. Typical Vapor Intrusion

The typical VI scenario is related to soil and groundwater contamination where vapors in the soil above the water table move into the overlying building's indoor air. Stakeholders intuitively understand how chemicals in groundwater pose a risk to drinking water; however, they may not have considered that volatile contaminants can transport through the soil and into their house through the gaps and cracks in a foundation slab, a basement, or other openings (e.g., sewer lines, sump pumps, etc.).

3.4.4.2. Conduit Vapor Intrusion Preferential Pathway

VI through utility corridors related to sanitary sewer lines, such as building plumbing and their related components like p-traps under sinks, is another way contaminated vapors can enter a building and impact the indoor air. If this pathway is responsible for elevated levels of contamination in indoor air, then mitigation will take another form, such as modifying the plumbing (see the **Vapor Intrusion Preferential Pathways Fact Sheet**).

3.4.4.3. Wet Basements

The presence of standing water from groundwater intrusion in basements and unsealed sumps can be a significant source of vapors to a building that stakeholders had not considered. While this is not VI, this concept is important to get across so that waterproofing and effective sump pump operation are encouraged and facilitated to mitigate the impacts of vapor from direct volatilization (see the **Direct Volatilization to Indoor Air Fact Sheet**).

3.4.4.4. Indoor Air Sources

3.4.4.4.1. Removing Background Sources for Sampling

Concerns over privacy may arise during the building survey, which is necessary for identifying and removing background sources. Often, the practitioner will request approval to access many areas of the home/workplace that are typically off-limits to the public, and this can induce stress. It is important to clearly explain the purpose of the building survey and the importance of thoroughness to avoid interference in the data from background indoor air sources. Approval to access each part of the property is essential to gaining trust. If photographs are taken, it is also important to first get approval from the occupant, focus photographs on the products potentially containing background sources, and walk through the photographs taken to assuage any privacy concerns. See **Appendix B: Example Documents** for example building surveys or the **Indoor Air Quality Questionnaire and Building Inventory Checklist** included with this guidance.

3.4.4.4.2. Background Sources of Vapor-Forming Chemicals

Communicating the concept of background sources and how they can interfere with indoor air results may be a difficult topic to discuss with property owners for many reasons. People are usually surprised to hear that the chemicals being measured in indoor air (that can potentially cause adverse health effects)

are also present in everyday products such as cleaning and craft supplies. It can seem like an invasion of privacy when asking about personal hobbies, taking inventory of products in a person's living or working space, and asking to remove identified products before conducting indoor air sampling. People may also be surprised to learn that environmental agencies do not regulate these indoor air sources even if they are causing an exceedance. The practitioner should explain potential background sources and how those sources will be compared to the indoor air contaminant levels during data evaluation as well as simple steps to reduce indoor air concentrations resulting from background sources. See the **Background Sources of Indoor Air Fact Sheet** for more information.

Mitigation systems operate by interrupting the subsurface to indoor air pathway and potentially, over time, reducing the subsurface contaminant levels. Interruption of the subsurface to indoor air pathway and the reduction of contaminant levels in the subsurface will not impact the indoor contaminant levels if those contaminants come from background indoor air sources. This concept needs to be explained to the occupant/stakeholder by the practitioner to avoid confusion. Be prepared to refer the occupant to information about reducing exposure to toxic consumer products, as well as safe ways to dispose of them. State or local health departments may have this information readily available.

3.4.4.4.3. Outdoor Air

Outdoor air can impact the health of the stakeholder by influencing indoor air contaminant levels. Outdoor air sources can include automobile emissions and point sources, including emissions from gas stations, manufacturing facilities, and dry cleaners. Furthermore, mitigation systems designed to reduce indoor air exposures cannot, in most buildings, lower indoor air levels of COCs below what is in the outdoor air. The practitioner should explain the average air contaminant levels in that region and how those levels will be compared to the indoor air contaminant levels during data evaluation.

3.4.5. Contaminants

The VI practitioner should ensure that information related to the VFCs for the site is clearly presented to the stakeholders. Practitioners may encounter a series of questions from concerned occupants regarding contaminants such as the following:

- What types of contaminants are present?
- Where did the contaminants come from?
- What were they used for?
- Are they still in use?
- What is being done to prevent further contamination if the chemicals are still in use?
- What is being done to clean up the contamination?
- How long will it take to clean up the contamination?

Additional information regarding chlorinated vs. petroleum compound impacted sites, and the screening of them, can be found in **Section 5.3 Step 2–Initial Vapor Intrusion Screening**.

3.4.5.1. Chlorinated Compounds

Chlorinated compounds require specialized sampling techniques and mitigation approaches that are often more complex due to the nature and persistence of these chemicals. The various types of chemicals and the products in which these chemicals appear should be presented to the building

occupants. It may prove useful to explain that some compounds transform into related, but still toxic, compounds in the subsurface.

3.4.5.2. Petroleum as a Unique Case Due to Degradation

Petroleum compounds pose health risks less often than other VFCs because they naturally break down in an oxygen-rich environment, such as when they migrate to shallow soil layers. Furthermore, petroleum compounds are commonly found in air because of their presence in vehicle fuels and exhaust. If completed pathways are found, the exposures will be managed in the same manner as other VFCs. If petroleum-contaminated properties are screened out of an investigation, without the need to collect samples, stakeholders may have additional questions as they are unlikely to understand biodegradation.

3.4.6. Sampling–Types and Uses of Samples

Sampling for VI tends to be more complex than sampling for other environmental exposures, and it usually requires the cooperation of, and may even require the participation of, building occupants and owners. Because of this relationship, the practitioner needs to gain access and build trust with the stakeholder prior to sample collection. It is essential that the types and purposes of sampling are thoroughly explained prior to sampling. The sampling scheme may differ from property to property, and this could cause some confusion or concern from the building occupant. In addition, there may be some significant concerns with privacy and disruption of and restriction to routine. The practitioner should listen to these concerns and approach sample collection with transparency, efficiency, and empathy. Additional information regarding sampling can be found in **Chapter 7: Sampling and Analysis** of this guidance document. To make it easier for stakeholders to understand indoor air and soil vapor sampling data, it is essential to present data and regulatory levels in consistent units, in most cases micrograms per cubic meter ($\mu g/m^3$).

It is important to explain the purpose of each form of sampling. Make sure stakeholders understand which sample results will indicate exposure that can lead to health effects, and which are investigative for forming the CSM. Some agencies use subsurface sampling to determine whether and where to sample indoor air, while others use it to determine whether elevated indoor air levels are the result of VI. In either case, stakeholders should be informed that soil vapor concentrations are almost always higher than indoor concentrations for each chemical, so they should not be compared against indoor air screening/action levels. Some states (e.g., Minnesota, New York) can make mitigation decisions based upon high soil vapor levels alone. Sample results should be communicated to the stakeholders in a timely, clear, and concise manner. It is essential that the data be presented in consistent units for each media type and that those units are clearly explained. Complexity in data communication may result in anxiety, mistrust, and frustration. See **Appendix B: Example Documents** for examples of sampling reports.

3.4.6.1. Types of Samples

3.4.6.1.1. Indoor Air

The number and location of indoor air samples tend to vary with the size and design of the building. In buildings with basements, it is common to sample both the basement and the ground floor. In any case, sampling requires multiple visits to the property of interest. Thus, it can be disruptive to the occupant. The appearance of the sample device(s) can cause anxiety and upset. The practitioner needs to clearly instruct the occupants on activities to avoid while indoor air sample collection is being conducted (e.g., indoor smoking) in order to promote the most accurate data collection. Clear signage with information including the purpose of the device (i.e., air sampling) and a point of contact is necessary to mitigate concern from uninformed passersby. Where real-time samplers are used, be prepared to answer questions about the results from stakeholders who are present.

3.4.6.1.2. Sub-Slab Vapor

Sub-slab soil vapor requires access similar to indoor air sampling but is more intrusive as it usually involves drilling a hole in a slab or floor. Care should be taken to avoid permanent, visible damage. Advance communication with the occupant during the process of selecting the sampling location can be key to gaining cooperation.

3.4.6.1.3. Soil Vapor

Exterior soil vapor sampling may be conducted in yards or sidewalks. While it is generally less disruptive than indoor or sub-slab sampling, care must still be taken to avoid damage to plants and landscaping.

3.4.6.1.4. Sewer Gas

Sewer gas may be sampled in nearby municipal sewer lines by lowering sensors or active/passive sampling vessels, such as passive sorbent tubes or tubing attached to active summa canisters, through manholes. This may cause temporary traffic disruptions and require the support of traffic control. Alternative techniques may include sampling sewer cleanouts or accessible vents or other fixtures within a building, which may feel intrusive to homeowners. See **Section 7.6.4** for a thorough description

3.4.6.1.5. Outdoor Air

Outdoor air sampling involves devices placed outside, often in conspicuous locations, on properties of interest. This can cause concern from the stakeholders related to perception and security. Therefore, it is important for the practitioner to work closely with the building occupant to identify technically appropriate and acceptable locations for sampling devices on the exterior of the building. Again, transparency in approach and clear signage is essential when performing air sampling.

Outdoor air may be impacted by nearby background sources, some of which, such as vehicle traffic or industrial operations, are time dependent. It may prove useful to discuss timing with stakeholders in advance.

3.4.6.2. Frequency and Duration

Different property types may require different sampling frequency and duration. Several factors inform these sampling schemes, including residential or commercial building use, current and/or future land use, types of receptors present, data required, and follow-up investigation. It is important for the practitioner to discuss these factors with the stakeholders so that the sampling scheme is understood, and the approach remains transparent.

3.4.6.3. Communicating Variability

Vapor results, particularly indoor air measurements, vary, sometimes by orders of magnitude, between sampling events and often within buildings. While VI practitioners may consider variability routine, those unfamiliar with VI may focus on the highest or lowest numbers as the basis for risk assessment and risk management decision. The practitioner should be prepared to explain the many factors that go into developing exposure estimates, including the number of samples used to estimate concentration, duration of data collection, timing, and building conditions. **Chapter 8: Data Evaluation and Vapor Intrusion Risk Assessment** provides further explanation. Where there is a high level of uncertainty, it may be helpful to have a conversation explaining that mitigation decisions may be conservative or even preemptive and not necessarily indicative of whether or not an unacceptable health risk has occurred.

3.5. Mitigation (Remedy Needed)

If conditions warrant mitigation, stakeholder concerns may shift to include questions about how to determine whether the system is working, worries about damage to their property, noise, and financial concerns about who will pay for systems and how property values may be affected. Table 3-2 lists specific concerns that a risk communicator should anticipate and be prepared to address during the mitigation phase. The table covers various mitigation types with possible concerns listed for each. See Chapter 10: Vapor Intrusion Mitigation for detailed technical information and ITRC's Risk Communication Toolkit (ITRC 2020b). The following sections summarize additional information that will help ensure successful communication with stakeholders throughout implementation of a range of mitigation types.

3.5.1. Everyone Is a Risk Communicator

It is important to consider that everyone involved in design and installation of a mitigation system becomes a risk communicator as they will be working in people's personal space. It is a good idea to make sure that everyone interacting with affected homeowners or other stakeholders is either trained to answer questions or has the contact information for a person who is available to answer stakeholder questions.

3.5.2. Mitigation Is Not the Same as Remediation

The difference between remediation and mitigation is not intuitive to most people. Stakeholders should be made aware that operation of a mitigation system does not inherently reduce or eliminate the presence of contaminants. Often, SSD systems are found, upon inspection, to be no longer operational due to the property owner's deliberate or accidental interference. Informing property owners of the long-term potential VI risk at their property may help to ensure ongoing system operation.

Additionally, informing stakeholders about what (if any) remediation efforts are being made and their timeline can help establish reasonable expectations for long-term operation of the mitigation system. Homeowners also need to be aware that if the remediation is successful, the mitigation may no longer be necessary to eliminate VI risk. Likewise, it is important to help them understand that complete cleanups are not always possible, and mitigation may still be needed after cleanup. Incorporating this understanding into the communication plan will facilitate execution of a smooth exit strategy without any surprises at the end.

3.5.3. Explaining Mitigation Systems

Practitioners will need to prepare for stakeholder meetings by thinking of ways to explain mitigation that are easily understood by owners and occupants. SSD systems are hard to explain to a stakeholder. For example, saying "vacuum barrier" may be more easily understood than SSD. If people are familiar with radon systems, it may be helpful to explain the similarities. Likewise, explaining system operation in terms of airflow (i.e., airflow out from the building/home rather than into) may be more easily understood than differential pressure.

Fact sheets with pictures will help stakeholders visualize how the system will work; online videos are particularly useful in helping stakeholders visualize the mitigation process. Explaining that the system will have a gauge so they can confirm that the system is working may ease anxiety. See sample VI mitigation fact sheets in Appendix B: Example Documents.

3.5.4. May Involve Cleaning Basements

It is not unusual for basements to be a storage area for massive amounts of personal or other property. It is important to work with the stakeholder to form a plan on how to make room for practitioners to complete their work. This should be done in advance of the mitigator's arrival to complete the installation.

3.6. Long-Term Stewardship Best Practices

A mechanism for future communication must be included if a site's closure strategy includes a VIMS or long-term monitoring. Different states will have different methods of addressing long-term management, and it may not always be handled by the responsible party. A future communication plan should outline how to address system issues, changes to the building, and ICs or ECs at property transfers or change of occupancy. Responsibilities for ensuring that systems are operating properly and successfully must be clearly outlined, particularly if responsibility rests with building occupants, residents, or managers. See **Chapter 11: Vapor Intrusion Component Determination, Exit Points, and Closure** for more information on curtailment and closure strategies associated with long-term stewardship.

At the time mitigation is proposed, it should be clear who is financially responsible for installation, initial OM&M, and long-term OM&M. Enforceable documents are recommended if responsibilities are split (e.g., responsible party performs installation and initial OM&M, and property owner performs long-term OM&M). Similarly, if monitoring is proposed, responsibility for sampling needs to be clearly outlined along with a mechanism to keep any future affected parties informed. These communication efforts will ensure continued access, if necessary, and continued protectiveness of the plan; they are also a mechanism to ensure future affected parties are informed.

For a mitigation system, a best practice is physically attaching pertinent information to the system in a visible location. Contact information, OM&M procedures, the closure letter, and a copy of the administrative controls that clarify responsibility for the long-term OM&M of the system are valuable information for future stakeholders.

Long-term sampling requirements will also vary somewhat by state. A document outlining why future sampling is necessary, what thresholds apply, and how the sampling will be conducted should be attached to the deed or otherwise made publicly available. Similarly, if the site's exit strategy involves revisiting homeowners or others where access was initially denied, details of how that will occur will need to be submitted to the regulatory agency; a good best practice is to include a short summary of why VI may be an issue to facilitate future communication.

If curtailment of a VIMS takes place, additional communication may be necessary. Active VIMS may provide occupants with a sense of safety. Reducing monitoring or converting an active VIMS to a passive VIMS or complete removal may raise the anxiety of the occupants, elevating the need to clearly communicate why it is no longer necessary. Communicating early about the possibility of curtailment can avoid surprises, but it is not always possible, particularly if occupancy or ownership has changed.

Over time, community interest in the VI response is likely to decline, particularly if there is turnover in the population. To maintain community engagement, it may prove useful to incorporate VI-related updates into ongoing environmental programs of local governments, regional health departments, or permanent nongovernmental organizations. The need for community involvement will likely diminish if remediation is conducted to remove the source. New construction on or near contaminated sites, as well as the repurposing of former industrial buildings, typically engages a larger group of stakeholders than investigating and mitigating existing buildings. Such sites may involve local officials, developers and property owners/operators, construction workers, future building occupants, and site neighbors. Sites

may be regulated as voluntary cleanups or brownfields or as hazardous waste sites, but sometimes there is no direct regulatory oversight.

In most cases, other than the redevelopment of single-family residences, the site triggers a desktop Phase 1 ESA or the equivalent. If that assessment suggests the possibility of historical releases of contaminants, such as the VOCs usually responsible for VI, an intrusive investigation, including subsurface sampling, such as a Phase 2 ESA is conducted. Once subsurface contamination is recognized, all stakeholder groups have a role to play in managing potential risks.

3.7. Development

3.7.1. Local Government

Concurrently, local governments are likely to use zoning approvals, permits, appropriations, and in some states, environmental reviews to manage development. Typically, local governments are not focused on the potential for VI when considering development projects. In most cases, they lack familiarity and expertise for evaluating indoor vapor risks. There have been instances where local governments have approved projects while being unaware of the potential for VI or without the authority to delay occupancy due to a potential environmental hazard. It is important for regulators and practitioners to proactively communicate with local permitting authorities when there is a concern for exposure to VFCs to educate as needed, identify gaps in authority, and collaborate on ways to overcome these obstacles for protection of public health.

Ideally, in municipalities with known VI concerns, the city engages with the environmental regulatory process. For example, in response to USEPA's request for a local ordinance, the City of Mountain View, California, in 2009 adopted a City Permit Process for the MEW Superfund Study Area, the site of one of USEPA's oldest and largest VI investigations. Among other requirements, the process directs city staff to consult with USEPA for proposed developments and certain remodeling within the Study Area, and it requires that "applicable EPA mitigations are reflected in the CEQA [California Environmental Quality Act] document and as Conditions of Approval in the Planning Permit" (Tsuda 2009).

This requirement led to the following finding by the city's Zoning Administrator pertaining to a residential development in the MEW VI study area:

> Prior to building permit issuance, the applicant shall work with City staff, the U.S. Environmental Protection Agency (EPA), and responsible parties to find adequate space on-site for appropriate design for improvements related to groundwater contamination remediation. Design of remediation equipment and placement will need to be reviewed and approved by all parties and a Certificate of Occupancy cannot be issued until final inspections have been completed by the U.S. EPA and the City of Mountain View. (Williams 2017, 2)

In neighboring Palo Alto, the city, the California State Lands Division Clearinghouse, Bay Area Water Board "established a mechanism for reviewing new building construction" at a Hewlett-Packard Superfund site, with the aim of preventing VI (USEPA OSRTI 2025). In fact, the Water Board published a fact sheet in 2022 "to provide developers, cities, homeowners associations, and the public a summary of expectations for development at properties where VI may pose a threat" (California Water Boards 2022, 1).

In March 2023, the City of Milwaukee, Wisconsin, experienced an evacuation of families from an industrial property redeveloped to a multifamily apartment building after discovery of TCE in indoor air two orders of magnitude above the target indoor air concentration (WDNR 2024). This situation prompted alders to amend a local ordinance that went into effect in January 2024 that requires the following for any property

being redeveloped from industrial to residential prior to issuance of a certificate of occupancy; this process is triggered by submittal of an application for occupancy (City of Milwaukee 2024):

- Review by the Health Commissioner
- Preparation and submittal of a Phase I ESA and Phase II ESA
- If VFCs identified, submittal of the following documents approved by the applicable regulatory agency:
  - Completed site investigation
  - Remedial action plan
  - Vapor mitigation plan
  - Vapor system commissioning
- Signed disclosure from the applicant indicating the presence or absence of environmental contamination and certifying the existence or lack of orders prohibiting occupancy.

3.7.2. Construction Workers

To the degree that construction workers are aware of the presence of VFCs on a site, they are primarily concerned that they will be exposed to VFCs during grading, trenching, or other earth-moving activities. Those concerns are typically addressed by (1) informing them of potential hazards and relative risk; (2) ensuring that they have appropriate hazardous materials training and personal protective equipment; and (3) on-site air monitoring is employed, if appropriate.

3.7.3. Future Building Occupants

Residents, students, employees, customers, churchgoers, etc. have a right to know whether their buildings have been subject to VI response, even if—hopefully—exposures are at acceptable levels. Some people may wish to avoid such buildings, even if assured by experts that the air is safe.

There are a small number of cases where prospective occupants are indeed notified. For example, in another part of Mountain View, the developer of a recently completed large apartment complex built on a former Superfund site with a history of VFC contamination incorporated a fact sheet into its rental agreements to inform prospective tenants about the site's history (California Water Boards 2023).

Notification is particularly important where building occupants have little choice over whether to spend time in a building. This would apply to residents of subsidized housing, public school students, and workers in some businesses.

3.7.4. Site Neighbors

It is fairly common for a new building erected under the oversight of an environmental regulatory agency, perhaps as part of a Brownfields or Voluntary Cleanup Program, to be subject to a thorough environmental investigation that leads both to the installation and operation of mitigation systems and even remediation of groundwater and soil vapor. Since such activities may be funded or led by entities that are not responsible for the release of the volatile substances, they are often not extended to neighboring properties.

For example, due diligence on the proposal to demolish the Police Credit Union building in San Francisco's Middle Sunset district led to the discovery in 2019 of a PCE soil vapor plume and indoor air

concentrations in the Police Credit Union building above state commercial screening levels. The site has been purchased by a developer of affordable housing, which, as of summer 2024, was in the early stages of construction. Only upon the insistence of neighbors were six homes sampled, and five were found to have concentrations of COCs above state residential screening levels. The neighborhood association is still seeking additional sampling, SVE at the now-vacant Police Credit Union property, and mitigation at any nearby home where PCE in indoor air exceeds the screening levels—excluding those with background sources. Neighbors believe that state regulators made a mistake by signing an agreement with the developer, absolving it of any responsibility for off-site contamination (Siegel 2021).

3.7.5. Long-Term Management

As with existing buildings, new buildings with mitigation systems may be subject to long-term OM&M. Where the operator of the building is *not* the developer, the developer's responsibility for OM&M should be passed to the operator. In large buildings, OM&M of VI mitigation can be integrated into building management systems. For example, at the Mott Haven school complex in the Bronx, New York, SSD systems are monitored by the schools' building maintenance system (Strauss and Siegel 2010).

To ensure that mitigation systems operate as long as needed to protect building occupants, it is common for a long-term site management plan to be prepared—and reviewed by regulators—before installation. This plan may place responsibility upon developers, building operators, building occupants, or all of the above. Where mitigation is carried out in the absence of regulatory oversight, developers and property owners should be encouraged to adopt similar management plans.

This portion of the page left blank intentionally. Next chapter begins on the following page.

CHAPTER 4: CONCEPTUAL SITE MODEL

4.1. Introduction

The CSM is the framework for assessing VI sources, pathways, and receptors that are likely to be affected by vapor migrating to indoor spaces. The goal of a CSM is to provide a description of relevant site conditions and potential vapor sources. The CSM is an iterative tool that should be developed and refined as information is obtained during review of the site history and continues throughout the site and/or remedial investigation until closure. The level of detail of the CSM should match the complexity of the site and available data. The CSM is a fundamental tool that is used throughout environmental site investigations, mitigation processes, and closure decisions. Its iterative development throughout the life cycle of a site project ensures that environmental risks, specifically related to VI, are understood and addressed effectively. To define the VI pathway as a complete exposure pathway, a VFC source, migration route, and receptor must be identified. The CSM is dynamically and routinely updated as new information is gathered during the implementation and monitoring of the mitigation measures. This allows for the evaluation of the effectiveness of the measures and the identification of any necessary adjustments. The terms *CSM* and *VI CSM* are used interchangeably throughout this chapter.

A CSM typically has three primary components:

1. **Vapor Source:** This is the origin of the contaminants, often linked to past industrial activities, leaks, or spills.
2. **Migration Pathways:** These are the routes through which contaminants travel, such as groundwater flow, soil vapor diffusion, or atmospheric movement.
3. **Receptors:** These are potential human or ecological receptors that might be exposed to contaminants. Receptors could include workers, nearby residents, groundwater users, or sensitive ecosystems.

The VI CSM helps to evaluate locations and types of vapor sources, subsurface vapor transport mechanisms, and the potential for a complete VI pathway; identify data gaps; and communicate findings and conclusions to other stakeholders. The CSM is more of a process than a final product. The CSM is essentially never complete. The CSM should be maintained and updated as new information is collected throughout the life cycle of the project including through mitigation design, mitigation performance, and mitigation curtailment. See the **Conceptual Site Models for Vapor Intrusion Mitigation Fact Sheet** for additional discussion on this topic.

The main purpose of the CSM is to do the following:

1. **Understand Contamination Risks:** It helps to visualize and understand the pathways through which contaminants move through the environment (e.g., soil, groundwater, air).
2. **Guide Decision-Making:** By summarizing available data, it serves as a decision-making platform for environmental investigations and mitigation efforts.
3. **Identify Data Gaps:** The CSM highlights the uncertainties or data gaps in site history, operations, geology, and the fate of contaminants, which can be addressed during future investigations.
4. **Evolve with the Project:** As data become available throughout the project life cycle, the CSM evolves to become more refined and accurate, providing an up-to-date understanding of the site's conditions.

The CSM should be based on available, reliable data describing the sources of the contamination and affected media, the release/transport mechanisms, the possible subsurface migration routes, and the

potential receptors, as well as historical uses of the site, cleanup concerns expressed by the community, and future land use plans. All the important features relevant to characterization of a site should be included in a CSM (e.g., depth to groundwater) and any irrelevant ones excluded (e.g., soil conditions well beneath the groundwater table). The CSM should present both a narrative and a visual representation of the actual or predicted relationships between the contaminants at the site and receptors (current and future building occupants), as well as reflect any relevant background levels.

A CSM provides a written and often pictorial summary of the soil vapor migration pathway from the vapor source to potential receptors, including site geology, hydrogeology, VFC distribution and composition, transport mechanisms, building conditions, and building occupants. The CSM should be supported by maps, cross sections, and/or site diagrams that provide a clear overview of the pathway. It is especially important that the site be reasonably well characterized for the purposes of sampling plan development (see **Chapter 6: Iterative Investigation Process**). The CSM is generally considered a living document and is often updated with new information and/or data throughout the life of a project (see Triad Approach, ITRC 2003). A narrative description should clearly distinguish what aspects are known or determined and what assumptions have been made in its development. The CSM should provide all interested parties with a conceptual understanding of the potential for exposure to compounds of concern at a site. It is an essential tool to aid investigation and soil vapor management decisions associated with the site and serves as a valuable communication tool internally and externally with the community.

4.2. Components of a Conceptual Site Model

The following section provides details on selected site information that make up components of a CSM. This list is not meant to be exhaustive but attempts to highlight the most common building blocks to the CSM. The components of the CSM build the picture of what the sources of the vapors may be, how they may be migrating both in the subsurface and in the building, and how receptors may be affected. This picture may be summarized both graphically and via a text summary. An example of a CSM and some of its components is included in **Figure 4-1.** An example like this helps display site use (**Section 4.2.2**), background sources (**Section 4.2.3**), receptor and risk scenario (**Section 4.2.4**), geology (**Section 4.2.13**), building characteristics (**Section 4.2.15**), and preferential pathways (**Section 4.2.16**). The sampling locations collected as part of a site investigation will build up the CSM and provide information on sources of vapors (**Section 4.2.5**), nature and extent of contamination (**Section 4.2.6**), soil (**Section 4.2.7**), groundwater (**Section 4.2.8**), soil vapor (**Section 4.2.10**), and indoor air (**Section 4.2.11**).

A robust CSM will typically include many of the components mentioned above and discussed in the sections below. Early versions of the CSM likely will have data gaps, which can be filled in and the CSM updated as investigations progress and data become available.

4.2.1. Site History

The site history should be reviewed to determine the type and location of potential releases of VFCs at the site. Analyzing past activities and operations at a location helps identify potential sources of contamination and the processes that may have contributed to any environmental issues. Understanding the site's history aids in determining where contaminants might have been released, guiding effective sampling and monitoring efforts. Additionally, recognizing past chemical uses can highlight potential risks associated with specific substances, ultimately informing decision-making in cleanup activities and regulatory compliance.

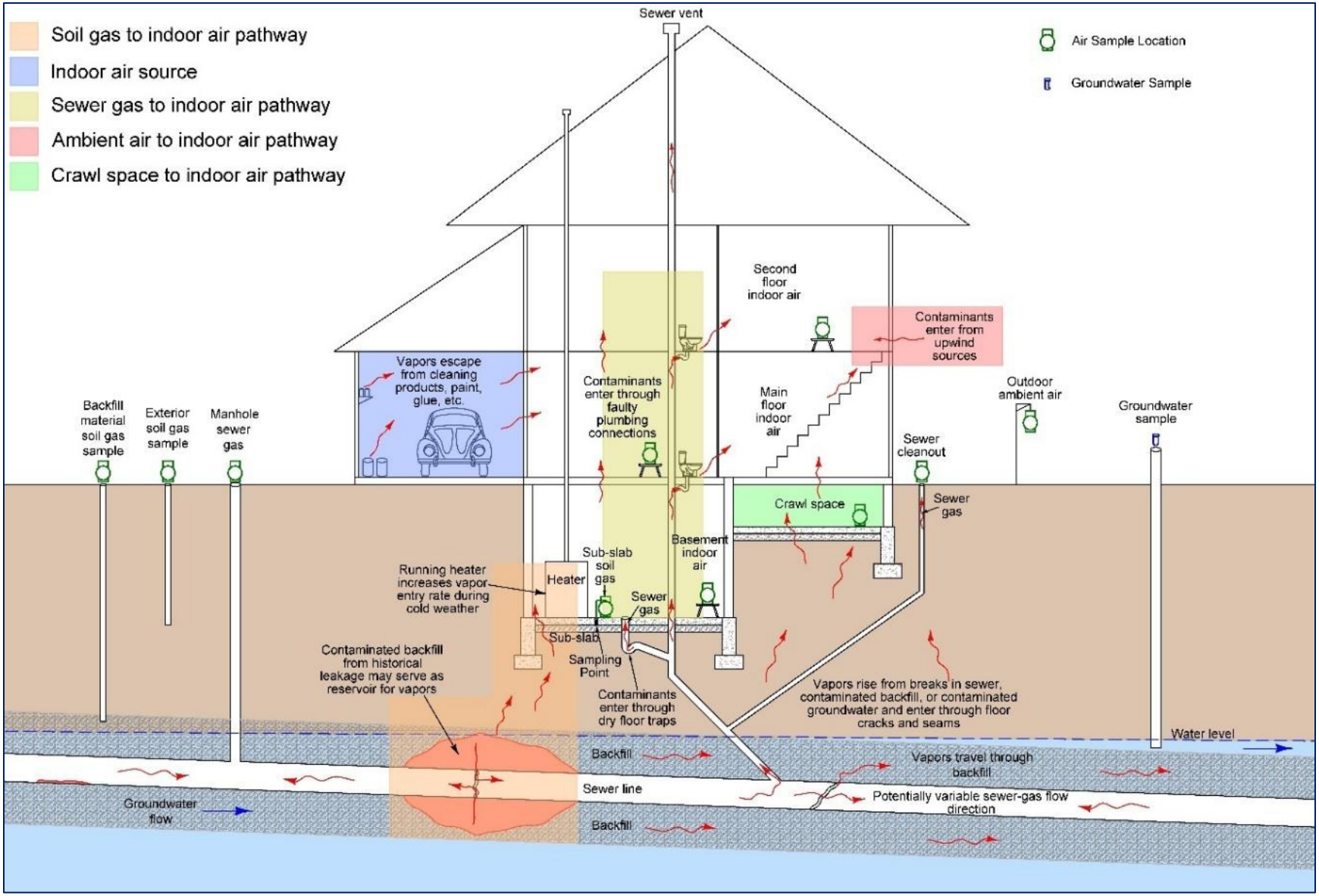


Figure 4-1. Example conceptual site model components displayed graphically.

Source: Laurie Chilcote, Association of Vapor Intrusion Professionals, used with permission.

Historical use information can be informative in the initial identification of potential sources of VFCs. Such information should not supplant the need for a thorough site assessment. Even historical environmental investigations with concentration data will likely require confirmation through an updated site assessment.

Historical data can indicate potentially used chemicals and their storage locations. Several resources may help with establishing which VFCs were used, manufactured, or stored on the site and where these activities occurred. Property records, city directories, aerial photographs, and historical maps are helpful for understanding the type and location of the release. Searching environmental databases such as states' databases, the USEPA hazardous waste cleanup location map (Cleanups in My Community | USEPA), the USEPA Emergency Planning and Community Right-to-Know Act, and USEPA Superfund records may help identify the types and sources of contamination at the site or at nearby properties. Interviews of previous or current site personnel, including owners and operators, may provide more information about the release's type and location. If the site is residential, interviews with current and former residents may provide more information on the history and environmental concerns. See **Chapter 3: Community Engagement** for more information about engaging with the public.

4.2.2. Historical, Current, and Future Site Use

Historical site use can be determined by reviewing historical records such as deeds, maps, or aerial photography or interviewing former employees, facility-specific personnel, or personnel from nearby facilities.

The current site use can be determined by reviewing the current ownership information or interviewing the current site personnel. Understanding current and historical site use will be one of the first components of the CSM and also one of the first steps in designing a VI investigation plan (see **Chapter 6: Iterative Investigation Process**) as this may help to understand where impacts were discharged and may likely be found. This review also allows practitioners to identify stakeholders who will be engaged throughout the VI project life cycle. See **Chapter 3: Community Engagement** for more information on interviewing and engaging with facility-related personnel and stakeholders.

Operations at a facility may have involved or currently involve the production, use, or storage of VFCs. VFCs may have been released to media including soil or groundwater, which can then volatilize to soil vapor. It is important to consider the current site operations and whether any background sources exist.

Future use and undeveloped lands present unique challenges in that the practitioner may need to account for those situations in how the CSM may change over time.

4.2.3. Background Sources

Background sources refer to indoor air levels of VFCs that are present in the absence of a release to the environment or in the absence of a complete VI pathway. See **Chapter 2: Vapor Intrusion 101** and the **Background Sources to Indoor Air Fact Sheet** for more information on background sources to indoor air and outdoor air. VFCs may be present in indoor air or outdoor air because of consumer products; supplies used for personal hobbies, household cleaners, paints, and building supplies; indoor or adjacent storage of VFC sources; residential heating fuels; household or building materials; and other sources. The CSM should include an understanding of what chemicals have been released into the subsurface and which are the VFCs with regard to the VI pathway. These VFCs may be both primary chemical constituents and their degradation products. If these VFCs are also suspected to be in background indoor or outdoor air, then this will affect the CSM for the site and will affect the way the site is investigated, how the data are evaluated, and potentially how the site may be mitigated. The **Background Sources to Indoor Air Fact Sheet** summarizes sampling strategies that can be used to collect data regarding background sources and data evaluation strategies used to evaluate their presence and impact on the VI assessment. In

addition, the Approaches for Vapor-Forming Chemical Source Determination Fact Sheet summarizes approaches that may assist with differentiating between background sources and potential VI contributions.

4.2.4. Receptor and Risk Scenario

Typical receptors are humans, both on and off the property, that may be exposed to site-related contaminants. Typical receptors include adults and children exposed in a residential setting, adults exposed in an occupational setting, and adults and children exposed in other nonresidential settings, such as schools, childcare centers, health care facilities, elder care facilities, businesses, or recreational areas. Section 3.4.2.4 has additional information about potential receptors.

Identification of possible receptors and exposure pathways can be evaluated based on the locality of the facility data, land use data, and demographics. Specific considerations might include the following:

- Future land use and surrounding area use
- Utilities in the area
- Zoning criteria (commercial, industrial, residential, or mixed-use areas that, for example, allow commercial on the first floor and multifamily residential on upper levels; some industrial zones allow a caretaker to live on the site; other commercial zones allow for uses such as childcare or elder care facilities)
- Land use constraints

One site may have multiple land uses, or the groundwater/vapor plume could extend across property boundaries to multiple properties, which could mean multiple receptors. Follow your state's guidance on documenting multiple land uses. If residential land use is one of the land uses, the standards and screening levels for the site need to be protective of residential land use.

Consider transport mechanisms and VIPPs when evaluating exposure to on-property and off-property receptors. Consider the risk to current and future on-property building occupants from soil vapor and/or groundwater plumes under the building. Consider the risk to off-property receptors if there is evidence that VFCs may be transported off-site via groundwater or soil vapor.

An evaluation of building occupancy scenarios should be conducted. Occupancy scenarios include evaluating building use (e.g., residential, commercial, industrial, schools, and day care) as well as potentially exposed populations (e.g., children or adults).

If the site does not currently have occupied buildings, but there are no controls to prevent occupancy, the VI to indoor air pathway should still be considered a complete pathway for a building occupancy scenario evaluation.

4.2.5. Sources of Vapor

The physical source of the contamination-producing vapors should be determined. The initial or primary sources (e.g., a leaking tank or a surface spill) or secondary sources (e.g., contaminated soil vapor, soil, or groundwater) may assist in the VI investigation. The following information should be gathered to assess likely sources:

- product type, chemical composition, and location of contamination
- contaminated media

- chemicals of interest present in each medium
- distribution and concentrations of contaminants in each medium

Part of the initial process of developing a preliminary CSM is identifying the VFCs that have been used at a site and/or released into the environment or are degradation products. In general, only compounds of sufficient volatility and toxicity are a concern for the VI pathway. Chemicals are often considered sufficiently volatile if its HLC is greater than 10^{-5} atmosphere-meter cubed per mole (atm m^3 mol^{-1}) or its vapor pressure is greater than 1 millimeter of mercury (mm Hg) (USEPA 2002). A compilation of HLCs can be found in USEPA's VISL calculator (USEPA 2024b) or compiled in online databases (Sander 2023). Common VFCs, such as TCE and benzene, meet both volatility criteria. USEPA's VISL provides a database of common chemicals that meet both volatility criteria and have adequate toxicity data. See the **Vapor Intrusion Screening Levels Calculator Fact Sheet** for more information.

VFCs may also directly volatilize into the building. This is not VI; however, it can result in exposure concerns that should be addressed. For additional information on this scenario, see the **Direct Volatilization to Indoor Air Fact Sheet**.

VFC source determination can be supported by environmental forensics, which can produce chemical fingerprints that are source specific. See the **Approaches for Vapor-Forming Chemical Source Determination Fact Sheet** for more information.

There may be other potentially explosive or toxic chemicals (e.g., methane and hydrogen sulfide) that can represent a subsurface soil vapor threat and should be investigated. If the VFCs do not meet these criteria, further consideration of the VI pathway is not warranted.

4.2.6. Nature and Extent of Contamination

Upon identification of a primary source or secondary source and the associated VFCs, the nature and extent of contamination in soils, groundwater, and/or the vadose zone should be assessed using the available information. In the preliminary CSM, VFC distribution and composition should be documented with a narrative description identifying what aspects are known or determined and what assumptions have been made.

As the CSM is updated, proper delineation of the VFCs in each medium, as discussed below, is critical in determining which buildings are in the lateral and vertical inclusion zone (see **Chapter 5: Site Screening** for more detail).

4.2.7. Soil

Soil data may be available from previous investigations and can therefore assist in the development of the preliminary CSM. Soil data may be used qualitatively to locate and characterize the source of contamination and the potential source of vapors, but it should be considered a LOE. Soil matrix data are generally considered less ideal for evaluating VI risk because of the small volume of soil used for analysis, the heterogeneous nature of soil contaminants, uncertainty associated with using partitioning equations to calculate soil vapor concentrations, and the potential loss of VFCs during sample collection. Numerous studies have identified sampling biases, and USEPA specifically has determined that the scale of the biases (both positive and negative) can be as large as several orders of magnitude (USEPA 1993a; 2014a). Scientific studies have failed to show a good correlation between soil vapor and soil analyses on a consistent basis.

4.2.8. Groundwater

Groundwater contaminant plumes migrating under or near buildings may be a vapor source. Groundwater characterization can provide groundwater flow direction; vertical and horizontal gradients, including seasonal variation, tidal influences, and the effects of groundwater withdrawal; the rate of groundwater flow; and the integrity of any confining units or other barriers to migration of groundwater. Groundwater characterization informs the understanding of plume dynamics and transportation for dissolved contaminants in groundwater and the potential for vapors to partition from the plume. Groundwater plume movement and its associated impact upon distance from the source to the receptor should be considered. Three factors that affect contaminant levels in groundwater in soil vapor are dispersion, dilution, and recharge.

The investigator may be asked to determine whether VI poses a risk beyond the known groundwater plume boundaries. Because of the distance interval between groundwater monitoring wells, it is often necessary during the early stages of CSM development to estimate the contaminant concentrations at locations that are closer to the building(s) of potential concern. Although the concentrations between monitoring wells may be interpolated based on the distance between the wells, it is generally safer to use the higher concentration found in the nearby wells initially to estimate the contaminant levels that may partition into soil vapor, possibly leading to VI. Also, since water concentrations at the top of the water table are a potential source of vapor partitioning, understanding the well construction and how groundwater samples were collected can be beneficial in making more accurate determinations. Concentrations at the air–water interface provide the best estimate for VI potential.

A clean water lens at the top of the saturated zone may effectively prevent VI even if higher concentrations are present at deeper intervals. Additionally, information regarding the groundwater flow direction and gradient is often useful in determining the potential for contaminant migration. It is important to note that the groundwater wells may not be installed for the purpose of assessing VI potential and therefore should not be your only measurement of VI risk. As the investigation progresses and the CSM is updated, additional monitoring wells to delineate the vertical and horizontal extent of groundwater plumes may be necessary.

4.2.9. Nonaqueous-Phase Liquids

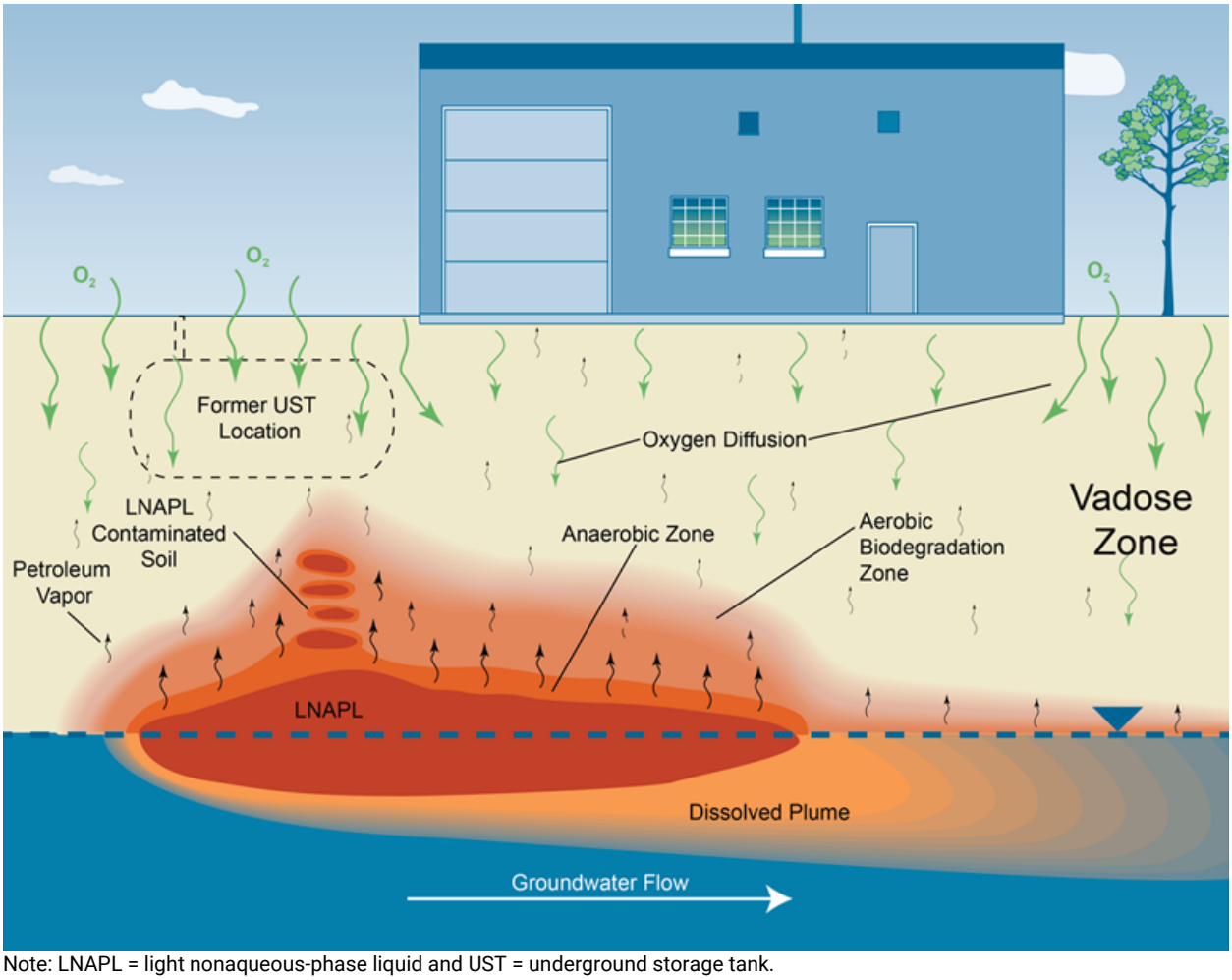
NAPL represent a distinct phase of organic liquid contaminants that are relatively immiscible in water. NAPL are generally characterized as LNAPL, which are less dense than water and typically remain near the top of the groundwater table, and DNAPL, which have greater density than water and typically migrate downward through the saturated zone until reaching low-permeability layers.

4.2.9.1. Light Nonaqueous-Phase Liquids

LNAPL typically remains near the top of the groundwater table and can serve as a persistent source of VFCs. LNAPL is typically derived from PHCs (e.g., gasoline, jet fuel, kerosene, and diesel—See **Appendix C: Chemistry of Petroleum**). Typical releases include breaches of pipelines, aboveground storage tanks (ASTs) or USTs, or surface spills. The presence of NAPL indicates initial concerns with dissolution to groundwater, the spread of LNAPL over the water table and direct volatilization thereof, and impacts to and transport though the groundwater media (**Figure 4-2**).

A typical LNAPL release consists of LNAPL fluid partially filling the soil pore space in a highly variable and often discontinuous distribution. The volume of aquifer occupied by an LNAPL body does not consist of a single fluid phase but rather consists of multiple fluids and soil in proportions that will vary throughout. An LNAPL body is therefore a multiphase system. LNAPL will be mostly located above the groundwater potentiometric surface, and spreading can occur both vertically and horizontally due to fluctuations in

groundwater elevations. Primary drivers of lateral migration are gradients within the NAPL lens from the initial release and the overall driving force of natural groundwater flow patterns.



Note: LNAPL = light nonaqueous-phase liquid and UST = underground storage tank.

Figure 4-2. A generalized representation of the elements of a light nonaqueous-phase liquid release and associated migration pathways.

Vapors emanating from an LNAPL source can produce an unacceptable risk to human health and the environment but are susceptible to aerobic biodegradation, given sufficient oxygen saturation within the soil and sufficient distance to attenuate. The LNAPL-impacted pore space contains varying quantities of LNAPL, groundwater, and/or gases both above and below the static water-table elevation. Generally speaking, the spatial extent occupied by an LNAPL body predominantly consists of water, followed by a lesser amount of LNAPL, with the smallest fraction of the pore space occupied by gas. This gas space is where vapor can form and provide a source of potential VI concerns. The predominant source area for VI due to LNAPL VI is located within the vadose zone along the capillary fringe and in the unsaturated zone where the LNAPL lens may have traveled in conjunction with groundwater fluctuations as well as the initial release area. This is where volatilization of VFCs can occur within the soil pore space and potentially produce indoor air concerns.

As mentioned above, LNAPL VFCs are typically subject to aerobic biodegradation and can attenuate readily over relatively short distances given clean soil above. Conditions will vary according to site type and the volume of the LNAPL release and extent of the LNAPL plume. In addition, natural attenuation of the LNAPL source area and associated vapors (i.e., natural source-zone depletion) can reduce both the mass in the source area and the vapors emanating from the source. Prior work (Davis, Patterson, and

Trefry 2009; Lahvis et al. 2013) has demonstrated that occupied buildings within a lateral distance of 30 feet from the LNAPL and within a vertical distance ranging from 13 to 15 feet at petroleum UST sites to 18 feet at a terminal, refinery, or petrochemical site should be further evaluated for VI. The presence of measurable LNAPL within a monitoring well, soil concentrations of TPH in gasoline range of 500 mg/kg, and/or photoionization detector (PID) or flame ionization detector (FID) readings greater than 500 parts per million (ppm) should be slated for further investigation. Sites with lower levels of LNAPL may be screened out (see **Section 5.4.1 Concentration-Based Screening**); however, consultation with the applicable regulatory authority is recommended prior to screening out these sites.

Soil vapor measurements of methane and carbon dioxide, as well as temperature, can also provide indicators of LNAPL source area and biodegradation. See **Section 7.6.3.1 Light Nonaqueous-Phase Liquid** for additional discussion on sampling options.

4.2.9.2. Dense Nonaqueous-Phase Liquids

DNAPLs, characterized by densities greater than water, include chlorinated solvents such as PCE and TCE. Unlike LNAPLs, DNAPLs tend to migrate vertically downward under gravitational forces, often penetrating deep into subsurface strata and accumulating atop impermeable layers such as clay or bedrock. Once pooled at depth, DNAPLs often represent persistent and challenging sources of VI concerns due to their resistance to natural attenuation processes. DNAPL releases typically originate from industrial processes, historical manufacturing facilities, dry-cleaning operations, and solvent storage or disposal areas. The assessment of DNAPL sources must consider vertical transport, diffusion of dissolved-phase chemicals, and vapor migration through preferential pathways. Due to their depth and persistence, DNAPL source areas often require detailed characterization and long-term management strategies to mitigate VI risks effectively.

4.2.10. Soil Vapor

Soil vapor data is recommended over most other media data, particularly soil and groundwater data, because soil vapor data represents a direct measurement of the contaminant that can potentially migrate into indoor air.

Soil vapor samples can be differentiated by the depth and location from which samples are collected. Near-slab soil vapor samples are collected outside a building but within a short lateral distance, typically within 10 feet of the building. Depths of these exterior soil vapor samples are typically at a depth between 3 and 5 feet, to avoid the effects of atmospheric pressure changes on soil vapor concentrations and to limit the potential for short-circuiting. Sampling depth may vary (deeper or shallower) on a site-specific basis. Sub-slab vapor samples are collected from below the building foundation or slab. Sub-slab vapor sampling is the preferred approach of many regulatory agencies for investigating VI, primarily because it represents the closest subsurface data to the receptor and is typically most representative of subsurface concentrations for evaluating VI risk.

Defining the nature and extent of subsurface contamination requires a sufficient number and location of soil vapor samples as well as an understanding of temporal and spatial variations in soil vapor concentrations. Guidance from several states, such as New Jersey (NJDEP 2021), provide a recommended number of soil vapor samples based on the square footage of the building. In addition, it is typically recommended to collect samples during both the heating and cooling seasons to evaluate potential temporal variations. For areas that do not have clear heating and cooling seasons and are more temperate throughout the year, it is recommended to collect samples during both wet and dry seasons to evaluate temporal variations. In either case, if soil vapor results from the initial sampling round are well above screening values, additional sampling to assess temporal variations may not be necessary. Assessment of additional areas may be necessary as the investigation progresses and the CSM is updated.

4.2.11. Indoor Air

Indoor air samples can include data from various indoor areas across multiple floors of the building (including basements and crawl spaces). Indoor air data often includes challenges associated with background sources that must be considered. Many commonly used household/industrial products (e.g., paints, dry cleaning solutions, carpeting, cigarette smoking, etc.) contain some of the same target VFCs, (see the **Background Sources to Indoor Air Fact Sheet**), and in some areas, especially urban centers, outdoor air concentrations may exceed allowable indoor regulatory levels. For these reasons, indoor air data must be evaluated carefully and are often collected along with other data such as outdoor air samples, building data, building operational information, building/chemical inventories (i.e., documentation of household products or other products stored or used), etc. It may also be appropriate, depending on the objectives of the sampling and the regulatory agency, to analyze indoor air samples for only the site-specific VFCs identified in the subsurface.

4.2.12. Degradation of Vapor

Vapor degradation in the subsurface is influenced by both biotic and abiotic processes. PHCs and chlorinated volatile organic compounds (CVOCs) experience similar partitioning. PHCs degrade more rapidly than most CVOCs due to aerobic microbial activity in the vadose zone, which can limit the potential for PVI. PHC vapors undergo biodegradation primarily through aerobic respiration, with oxygen acting as the electron acceptor. Factors such as soil moisture, oxygen availability, temperature, and presence of heavy metals can impact the biodegradation process. In contrast, most CVOCs degrade more slowly under anaerobic conditions, often producing daughter compounds that may be more hazardous. Including these degradation processes in the CSM is critical when assessing VI pathways at contaminated sites.

4.2.13. Geology and Hydrogeology

Site geology and hydrogeology impact the distribution and communication of vapors in the subsurface. Fractured rock and rock with natural conduits such as karst (limestone with cracks and holes from the dissolution of limestone with water) can rapidly transport impacted water and vapors over short to long distances. Clay may impede the migration of vapors depending on the depth of the clay in relation to the VFC mass and the continuity of the clay layer. Clay may not impede vapors if the clay is immediately under the building and the VFCs were released into the clay under the slab (Lutes et al. 2021). This example highlights the importance of understanding subsurface soil conditions at the particular site or building.

A narrative description, maps, cross sections, and site diagrams should clearly distinguish what aspects are known or determined and what assumptions have been made in CSM development. Data on site geology and hydrology (e.g., soil moisture and porosity) to support the interpretation of soil vapor profiles, the characterization of subsurface gas permeability, and the identification of anticipated soil vapor migration routes in the vadose zone or the identification and characterization of impeded migration are important considerations in CSM development and in the design of any mitigation strategy (see the **Conceptual Site Models for Vapor Intrusion Mitigation Fact Sheet**).

4.2.14. Climate and Weather

Local and regional climate and weather conditions can influence the VI pathway through natural fluctuations in environmental conditions, including but not limited to changes in temperature, barometric pressure, wind speed and direction, and precipitation (Eklund 2024; USEPA 2015a). Changes in weather conditions are often discussed in the CSM as a potential cause of short-term (e.g., diurnal) to long-term (seasonal) variations in indoor air and soil vapor concentrations.

For example, the stack effect (or chimney effect) refers to the natural transport of air into, within, and out of buildings due to differences in indoor and outdoor air temperature. The stack effect is often cited as a potential cause of seasonal changes to indoor air concentrations (e.g., Johnson et al. 2016; USEPA 2012a) and is most pronounced in colder months when indoor-outdoor temperature differences are greatest (USEPA 2015a). Building- and site-specific relationships between indoor air concentrations and other environmental conditions have been observed and reported in the literature (Kram and Solgi 2025; Schuver et al. 2018; USEPA 2012a).

Seasonal changes can also affect building operation and occupancy behavior, including the use of HVAC systems, which in turn may alter pressure differentials and building air exchange rates. Similarly, changes in precipitation can lead to changes in groundwater levels, which may influence the migration and attenuation of vapors in the subsurface.

4.2.15. Building Characteristics

Information regarding the construction, design, and operation of a building may be used in the CSM to assess the likelihood of subsurface soil vapor entering the building. Several building factors are typically considered during VI assessments, including foundation or slab type and integrity, the presence and condition of basements or crawl spaces, building age, and the types of materials used in construction. As discussed further in **Section 4.2.16** and the **Vapor Intrusion Preferential Pathways Fact Sheet**, features such as sumps, foundation drains, elevator shafts, and utility conduits and slab penetrations can serve as entry points for vapors originating from underlying soil or groundwater. Existing vapor barriers can inhibit the entry of soil vapors, depending on the extent and condition of the barrier, how well they are sealed to the foundations, and the likelihood that they will be maintained in the future.

HVAC systems can also influence VI potential. HVAC operation can alter indoor air pressure relative to the subsurface, directly impacting vapor entry rates. For example, positive indoor air pressure may reduce soil vapor migration into buildings, whereas negative indoor air pressure may enhance VI by creating conditions favorable for advective flow through foundation openings or utility penetrations. In buildings with multiple HVAC systems, individual HVAC zones may function independently or be managed differently, resulting in varying conditions that require separate consideration during CSM development.

Older and existing buildings with compromised foundations or slabs, deteriorated basement walls, or unsealed crawl spaces may exhibit higher vulnerability to VI compared to newer, well-maintained buildings.

Additional guidance on building characteristics to consider during CSM development is provided in the **Building Characteristics Fact Sheet**.

4.2.16. Preferential Pathways

Preferential pathways, in general, are pathways that intersect both the vapor source and the building foundation and provide for an increased flow of vapors that is higher than expected under typical conditions (i.e., typical vapor transport through vadose-zone soils). They are important to the CSM as, if they exist at a site, they may help to define the extent of the area that needs to be evaluated for VI. It is important to distinguish between VIPPs that enhance the migration of vapors over potentially long distances and the vapor entry point, which is the location where VFCs may enter the building. The **Vapor Intrusion Preferential Pathways Fact Sheet** provides terminology to describe a conduit VIPP, a vertical VIPP, vapor entry points, and what may be considered direct volatilization (see the **Direct Volatilization to Indoor Air Fact Sheet**). The fact sheet also discusses CSM indicators that may increase the likelihood of the presence of VIPPs, whether VIPPs may present a precluding factor (for example when using distance-based screening), and where and how to sample, if needed. The influence of VIPPs should be considered

within all stages of the CSM including the preliminary CSM, the investigative CSM, and the mitigation CSM.

At the beginning of a project, assessment of the VI pathway typically focuses on the nature and extent of VFC impacts in soil and groundwater. Screening distances (see Section 5.3.2) are typically used consistent with the idea that the closer the potential receptor is to impacted soil or groundwater, the higher the potential for VI. For that reason, VI pathway evaluations typically take place over the footprint of impacted areas, plus a conservative buffer. If, however, a sanitary sewer, or other conduit, intersects a source in groundwater (or impacts are introduced directly to the conduit), there is potential for a conduit VIPP, in which contaminants enter the conduit, to allow vapors to flow in a direction outside the typical area of VI assessment. See the Vapor Intrusion Preferential Pathways Fact Sheet for more information.

4.2.16.1. Using Components of a Conceptual Site Model as Lines of Evidence

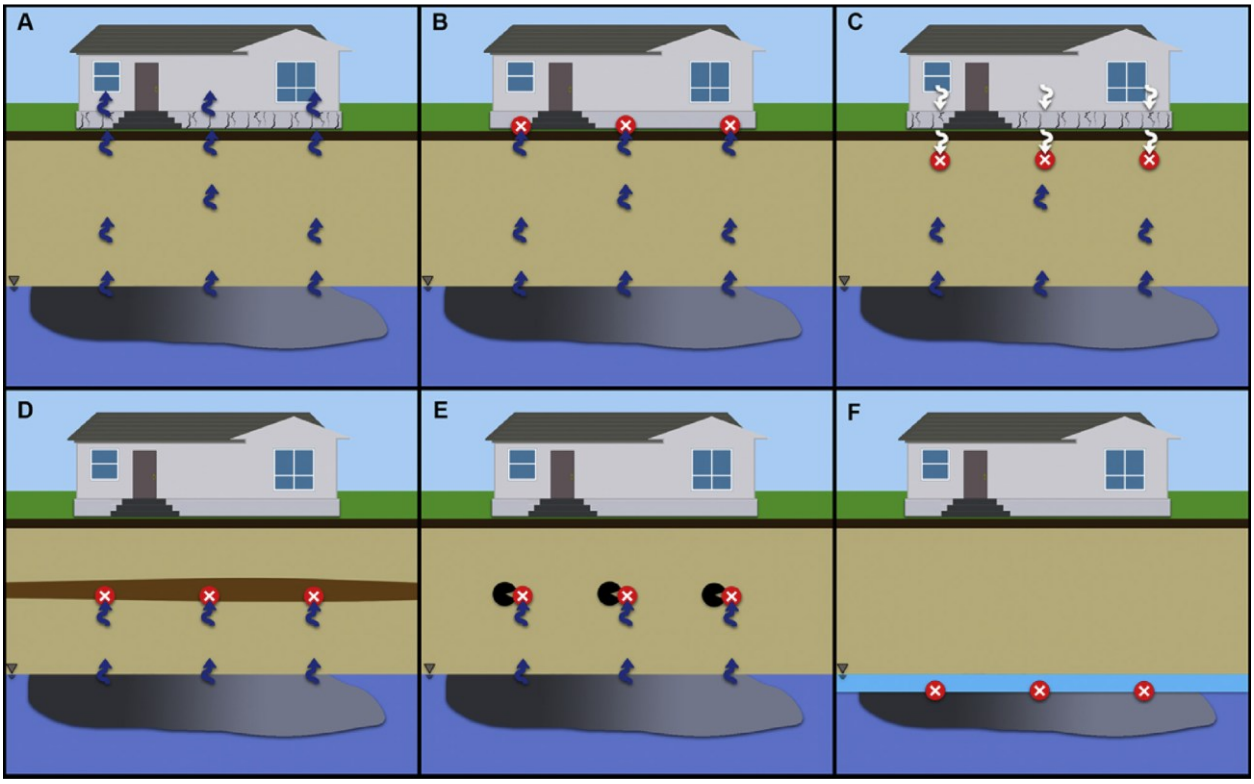


Figure 4-3. Potential barriers to vapor intrusion: (A) no barriers, (B) impermeable building foundation, (C) positive building differential pressure, (D) saturated clay/silt layer between vapor source and building, (E) biodegradation of vapors in the vadose zone, and (F) clean water lens at the top of the water table.

Source: McHugh et al. (2017), used with permission.

The components of the CSM can provide MLE regarding the potential for VI. For example, a VFC vapor source, transport pathway, and presence in a potentially occupied building are all necessary to confirm that VI is occurring. As defined in the Multiple Lines of Evidence Fact Sheet, a LOE is a piece of information that is used to help create an understanding of the VI pathway. One LOE is unlikely to be sufficient to confirm or rule out the potential for VI; for example, detection of a VFC in indoor air could be due to VI, a background source, or both. The presence of the same VFC in sub-slab vapor might increase the likelihood that VI is the source of the VFC in indoor air, but the absence of another VFC in indoor air that is present in sub-slab vapor (considering that attenuation across the slabs should be consistent for

both VFCs) would indicate that a background source was more likely. Therefore, MLE are usually needed to answer questions related to the potential for VI at a building. MLE are components of the CSM and are used to support the characterization of site conditions, which then furthers the understanding of the potential for VI, presence of any VI pathways, and potential VI risk to receptors through MLE. Components of the CSM can be MLE that may support the potential for VI or may highlight potential barriers to VI. An example of some of the various CSM MLE components that highlight barriers to VI are shown in Figure 4-3.

An example of a CSM component that also may be used as MLE is knowing current and historical building use. This information is typically part of the CSM but also may help understand whether, for example, there are background indoor air sources. Building use that suggests the presence of background indoor air sources is an MLE that could support the conclusion that the VI pathway is not of concern and the presence of VFCs in indoor air are due to current or historical VFC use in the building. Alternatively, for example, historical building use may indicate the location of a former degreaser, and this would be MLE supporting the likelihood of a VI along with concentration data. A more complete discussion of MLEs is included in the Multiple Lines of Evidence Fact Sheet.

4.2.16.2. Conceptual Site Model Stages

The development of a CSM evolves in stages, with each stage serving a distinct purpose in site investigation, mitigation, and post-mitigation phases. The primary stages are listed below (USEPA 2012d):

5. **Preliminary CSM Stage**
    - **Purpose:** Develop an initial representation of the site based on existing data (e.g., historical records, site inspections).
    - **Objective:** This stage occurs prior to any systematic data collection or planning efforts and is used to establish an initial understanding of the site's potential risks.
6. **Baseline CSM Stage**
    - **Purpose:** Provides a clearer site representation that can be shared with stakeholders to gain consensus.
    - **Objective:** This stage helps identify data gaps and uncertainties. It is part of the systematic planning process and establishes a baseline understanding of the contamination at the site.
7. **Characterization CSM Stage**
    - **Purpose:** The CSM is continually updated as new data are gathered from site investigations (e.g., sampling, monitoring).
    - **Objective:** This stage supports decisions related to selecting a mitigation strategy and assessing the effectiveness of the cleanup effort.
8. **Design CSM Stage**
    - **Purpose:** Focuses on refining the CSM to support the design of the mitigation strategy.
    - **Objective:** Updates to the CSM are targeted to support decisions regarding the types of remedial technologies and approaches to be used at the site.
9. **Mitigation CSM Stage** (see Conceptual Site Models for Vapor Intrusion Mitigation Fact Sheet)
    - **Purpose:** Continually update the CSM during the implementation of the chosen mitigation methods.
    - **Objective:** The CSM at this stage is critical for tracking the progress of cleanup efforts and confirming the attainment of cleanup objectives.

10. **Post-Remedy CSM Stage**
    - **Purpose:** After the primary mitigation activities have been completed, the CSM supports planning for site reuse and potential ICs.
    - **Objective:** It helps identify any remaining risks, ensures proper long-term management, and supports decisions regarding site reuse or future monitoring.
11. **Complete CSM Stage**
    - **Purpose:** Documents the comprehensive model of current and future site conditions for VFC source, pathway, and receptors
    - **Objective:** Supports the closure of the VI project

Community engagement (see Chapter 3: Community Engagement) is a critical component throughout the entire life cycle of a CSM, from its initial development to its ongoing refinement post-implementation. Engaging with affected communities at the outset ensures that local knowledge, concerns, and priorities are incorporated into the CSM, fostering trust and collaboration. As the site progresses through various stages—including assessment, investigation, mitigation, and monitoring—active communication with stakeholders allows for transparency and responsiveness to evolving issues. Revised engagement plans should be developed and updated periodically, as each phase may introduce new stakeholders, challenges, or opportunities for further outreach. This iterative approach ensures that community input remains valued and that the CSM adapts to the changing landscape of stakeholder perspectives and community needs, ultimately enhancing the effectiveness of mitigation efforts and promoting sustainable environmental stewardship.

4.3. Refining the Conceptual Site Model

An accurate and well-maintained CSM is essential for ensuring the success of environmental site management efforts:

- **Informed Decision-Making:** It helps guide the project team in assessing risks, planning investigations, and designing mitigation efforts.
- **Stakeholder Communication:** It provides a clear and visual representation of site conditions for regulators, the public, and other stakeholders.
- **Risk Management:** Understanding the source, pathways, and receptors allows for effective risk management and mitigation strategies.

The CSM should not be viewed as a static document but rather as an evolving tool that reflects the increasing understanding of the site as new data are collected and analyzed. This iterative process makes it possible to adapt the project strategy to address emerging issues and uncertainties.

In summary, the CSM is both a dynamic tool and a vital component for effectively managing environmental risk at contaminated sites, providing a framework for investigation, mitigation, and post-mitigation activities.

The CSM should be refined and updated as new information is gathered throughout the site investigation and mitigation process. Refining the CSM is important for several reasons, including the following:

1. **Refines the understanding of the site:** As new data are collected, the CSM can be updated to reflect the evolving understanding of the site conditions, contaminant sources, pathways, and receptors.

2. **Identifies potential data gaps**: Refining the CSM can help to identify data gaps or uncertainties that need to be addressed through additional investigation.
3. **Supports decision-making:** An up-to-date CSM provides a solid foundation for making informed decisions regarding site management, including the selection and implementation of remedial actions.
4. **Facilitates communication:** A well-developed CSM can help to communicate the site conditions and potential risks to stakeholders, including regulators, property owners, and the public.

Refining the CSM typically involves the following stages:

1. **Review new data:** Gather and review new data during site investigations, monitoring programs, and other sources.
2. **Update the CSM:** Incorporate the interpretation of new data into the CSM, including any changes to the identified sources, pathways, and receptors.
3. **Evaluate the CSM:** Assess the updated CSM to determine whether it adequately represents the current understanding of the site.
4. **Identify data gaps:** Identify remaining data gaps or uncertainties that need to be addressed or new data gaps that have been discovered.
5. **Develop a plan:** Develop a plan for addressing data gaps and uncertainties, including additional investigation or monitoring activities.
6. **Communicate the CSM:** Document the changes made and share the updated CSM with stakeholders.

By refining and updating the CSM, stakeholders and the community can be reassured that the site is being managed in a way that is protective of human health and the environment.

This portion of the page left blank intentionally. Next chapter begins on the following page.

CHAPTER 5: SITE SCREENING

5.1. Introduction

VI screening assesses (1) whether VI can occur due to VFC sources in the subsurface, (2) the current or future buildings where occupants could potentially be exposed (receptors), and (3) the complete pathways between the source and building foundation. The goal of VI screening is to determine whether the potential for VI exposure warrants further evaluation, mitigation, or remediation or if VI exposure can be ruled out based on a limited or preliminary VI CSM. Not all VI sites require detailed and comprehensive CSMs. For example, PVI sites can often be screened out simply based on source–building separation distance (i.e., pathway evaluation). VI screening is also used to identify the presence of VI conditions that warrant an emergency or rapid response.

The VI screening process follows a three-step approach as explained below and outlined in **Figure 5-1**:

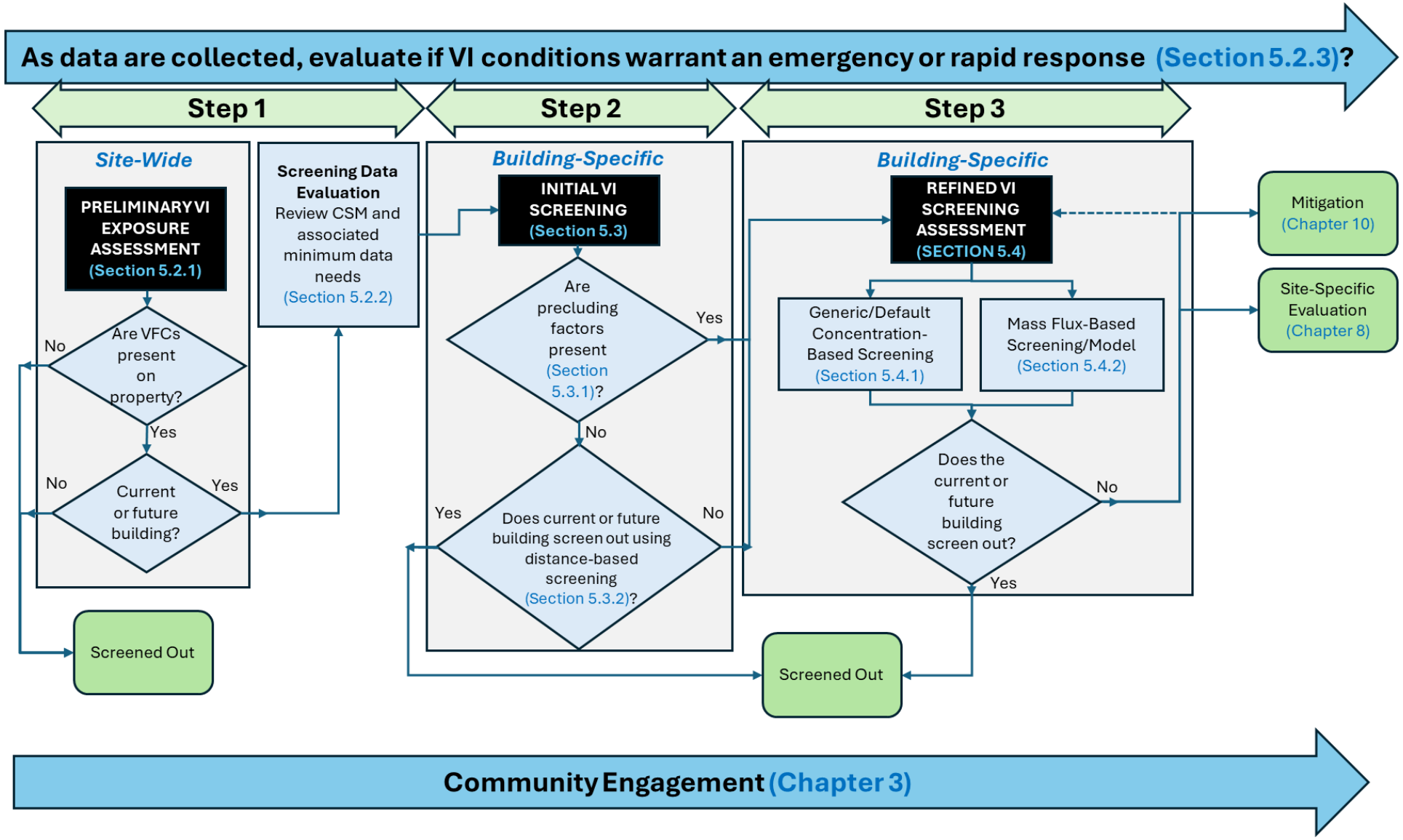
1. **Step 1: Preliminary VI Exposure Assessment** (Section 5.2).
   This step documents the presence of VFCs in the subsurface and potential linkage between the VFC source and a current or future building across a site.

2. **Step 2: Initial VI Screening** (Section 5.3)
   This step involves a further review of the current CSM to assess whether there is sufficient data to perform VI screening (screening data evaluation) and whether precluding factors are present (precluding factor assessment) that prevent the application of screening distances. If no such factors are present, current or future buildings on-site are evaluated using distance-based screening.

3. **Step 3: Refined VI Screening** (Section 5.4)
   This step uses more refined methods based on generic or default concentration-based screening or mass-flux-based screening to assess whether VI potentially occurs within the current building or could occur in future buildings.

Although the three methods described in this section are scientifically and technically defensible for VI distance-based screening, concentration-based screening, and mass-flux-based screening, it is important to consult with the local regulatory agency to determine whether a given method or particular media (e.g., indoor air in the case of concentration-based screening) can be used to screen out a building from further VI assessment.

The three possible outcomes of VI screening are (1) site conditions warrant emergency or rapid response, (2) no further VI evaluation is necessary, or (3) a more detailed evaluation (see **Chapter 8: Data Evaluation and Vapor Intrusion Risk Assessment**) or mitigation or remediation (see **Chapter 10: Vapor Intrusion Mitigation**) must be undertaken.



Note: CSM = conceptual site model, VFC = vapor-forming chemical, and VI = vapor intrusion.

Figure 5-1. Generalization of vapor intrusion screening process.

5.1.1. Screening Requirements

Certain key information and site data are needed to perform VI screening. These data are generally obtained during a Phase I investigation (e.g., to assess the potential for historical releases of VFCs to the subsurface or at nearby properties and conduct a property inspection) and during a preliminary site investigation that would target the distribution of VFC sources in the subsurface and assess the presence and occupancy of current and future buildings. The amount of information needed to perform VI screening varies depending on the complexity of the VI CSM (potential sources, pathways, and receptors) and screening method (e.g., distance-based, concentration-based, or mass-flux-based screening). It is therefore important to review the minimum data requirements of each screening method prior to implementing Steps 2 or 3 of the VI screening process.

5.1.2. Conservatism in Vapor Intrusion Screening

VI screening incorporates conservative assumptions designed to account for uncertainties in VI exposures caused by site conditions that can vary spatially and temporally. Such variability is often not fully documented at the preliminary VI CSM stage. This data gap is acceptable at the VI screening step, with the understanding that the assumptions, variables, and thresholds used to define distance, concentration, and mass-flux-based screening are intended to account for the variability and minimize false negatives (i.e., incorrectly concluding there is no VI risk when one actually exists).

5.2. Step 1–Preliminary Vapor Intrusion Exposure Assessment and Screening Data Evaluation

Step 1 consists of a preliminary VI exposure assessment to determine whether VI is possible, and if it is, to conduct a screening data evaluation to identify the most appropriate method for VI screening and to identify the associated data needs for application of the method. The preliminary VI exposure assessment targets the site or property where contaminants are present in the subsurface. The screening data evaluation and subsequent screening steps (Initial VI Screening—Step 2 and Refined VI Screening—Step 3) target current or future buildings of concern for VI.

5.2.1. Preliminary Vapor Intrusion Exposure Assessment

The preliminary VI exposure assessment serves as an initial determination of whether there is a potential for VI using two primary criteria: (1) the known or suspected presence of VFCs in the subsurface (e.g., soil, groundwater and/or soil vapor) based on sampling data and/or information about current and historical site and chemical use (on-site and adjoining properties) and (2) the presence of current or reasonably anticipated future buildings and land use. If both of these conditions are present, then additional VI screening is required, beginning with a screening data evaluation (see **Figure 5-1**). No further VI evaluation is necessary (the site screens out) if VFCs are not present or suspected in the subsurface. If VFCs are present or suspected, then further VI evaluation is required (**Section 5.2.2**) provided (1) contamination is not migrating and (2) building(s) are not present and site use and construction of future buildings is restricted.

5.2.2. Screening Data Evaluation

The screening data evaluation is performed to ensure that the VI CSM contains sufficient information to perform VI screening. To meet this objective, it is critical to review the methods (or options) for VI screening described in Steps 2 (**Section 5.3 Step 2–Initial Vapor Intrusion Screening**) and 3 (**Section 5.4 Step 3–Refined Vapor Intrusion Screening**) and their associated data needs. Such data may already exist at certain sites but not at others. If the VI CSM is incomplete for VI screening, further data collection

targeting minimum data needs for Steps 2 and 3 will be necessary. It is important to understand these key points:

- Buildings can be screened out without a comprehensive VI CSM or vapor data in certain cases (e.g., distance-based or certain mass-flux-based screening).
- Substantial data collection and analysis are often necessary to support VI decision-making at sites or buildings that do not screen out.

The minimum data required for screening are described in **Section 5.3.2.2**, **Section 5.4.1.2**, and **Section 5.4.2.2**. Practitioners should weigh the benefits and challenges of each VI screening method before deciding on a method for VI screening. For example, depressurization methods for mass-flux-based screening can be used to rapidly diagnose VI occurrences and have very few data needs; however, these methods are relatively sophisticated and generally require experienced practitioners to implement. In addition, any site-specific data collected at this and subsequent stages of CSM development must undergo thorough quality assurance / quality control (QA/QC) to support confident and proper VI decision-making (see **Data Quality and Adequacy Fact Sheet**). Lastly, it is important to align with the applicable regulatory oversight agency on the appropriate method for VI screening. Although all the methods described in this section for VI screening are scientifically and technically defensible, they may not be accepted by the applicable regulatory agency.

5.2.3. Evaluation of Emergency or Rapid Response

Emergency or rapid response actions may be necessary when data collection shows these conditions:

- **Fire and explosion hazards:** methane or flammable hydrocarbon vapors in indoor air or sub-slab soil gas that exceed flammable concentration limits (e.g., LEL for methane)
- **Acute health risks:** elevated concentrations of chemicals, such as TCE, PCE, elemental mercury, or PHCs in indoor air that could lead to acute health effects on building occupants
- **Wet basements**: groundwater containing VFCs has entered a building basement
- **Building occupant complaints of odors or physiological effects:** occupants complain of chemical, solvent, or gasoline odors or dizziness, nausea, vomiting, confusion, etc. (note—the presence of odors or physiological effects does not necessarily indicate VI is occurring; the odors could be the result of background sources in indoor air)

Emergency and rapid response generally involve data with the following attributes:

- Identify and target potential vapor sources, migration pathways, buildings, and potential exposures to workers or residents
- Are compared to established emergency thresholds for chemicals that contribute to explosive or toxic exposure risks
- Are measured using real-time screening instruments that allow for immediate decision-making in the event of elevated vapor concentrations, such as the following:
    - Combustible gas indicators that measure flammable gases (e.g., methane, petroleum vapors) to assess fire/explosion risk
    - PIDs and FIDs that measure VOCs in indoor air
    - Field gas chromatography (GC) equipment that measures concentrations of VFCs that may be immediately harmful to human health

- Multi-gas meters that measure multiple gases (e.g., VOCs, carbon dioxide, and oxygen) in air simultaneously
- Portable fluorescence spectroscopy analyzers that measure mercury in indoor air

Emergency or first responders (fire departments, hazardous materials teams) should be consulted whenever emergency or rapid response conditions are encountered. Such persons are used to inform data collection and immediate actions, occupant evacuation and re-entry, and long-term mitigation planning. More information on emergency and rapid response can be found in the **Rapid Response and Ventilation for Vapor Intrusion Fact Sheet**.

5.2.4. Community Engagement

During the site screening process, it may be necessary to inform and/or communicate potential VI risks to building occupants, owners, or responsible parties. More information about public outreach and community engagement is provided in **Chapter 3: Community Engagement**.

5.3. Step 2–Initial Vapor Intrusion Screening

VI screening is generally performed sequentially beginning with initial VI screening (Step 2) to assess whether site conditions are favorable for VI screening (precluding factor assessment) and, if so, whether current or future buildings can be screened out based on distance-based screening (i.e., a potential VI exposure pathway is present). Any buildings that do not screen out based on source-building separation distance are then subject to refined VI screening that involves either concentration-based or mass-flux-based screening (Step 3). A robust CSM may not be required at this stage. The CSM must, however, contain sufficient information to support the VI screening used.

5.3.1. Precluding Factors Assessment

Before conducting the VI screening, it is important to identify the presence of certain site-specific factors or conditions that preclude or prevent VI screening, in particular, the following;

- VFC plume in soil or groundwater located outside the lateral screening distance (or lateral inclusion zone) that could enter the lateral inclusion zone in the future
- VIPPs (see the **Vapor Intrusion Preferential Pathways Fact Sheet**), such as sewer laterals, utility conduits, and fractured rock that directly connect the VFC source in soil or groundwater to the current or future building foundation (i.e., the preferential pathway intersects both the VFC source and building foundation)
- PVI sites have either of the following:
  - Large buildings (exceeding 66 feet [20 m] in both length and width) above LNAPL sources (USEPA 2013)
  - Vadose-zone soils containing high fractions (e.g., > 4%) of organic carbon (e.g., peat) or excessively low moisture content (e.g., < 2% vol/vol) (e.g., desert soils unable to sustain plant life) (Holden et al. 1997; Leeson and Hinchee 1996)

A migrating VFC groundwater plume located outside the lateral screening distance (or lateral inclusion zone) that could enter the lateral inclusion zone in the future is not a precluding factor for screening current conditions but is a precluding factor for future VI screening.

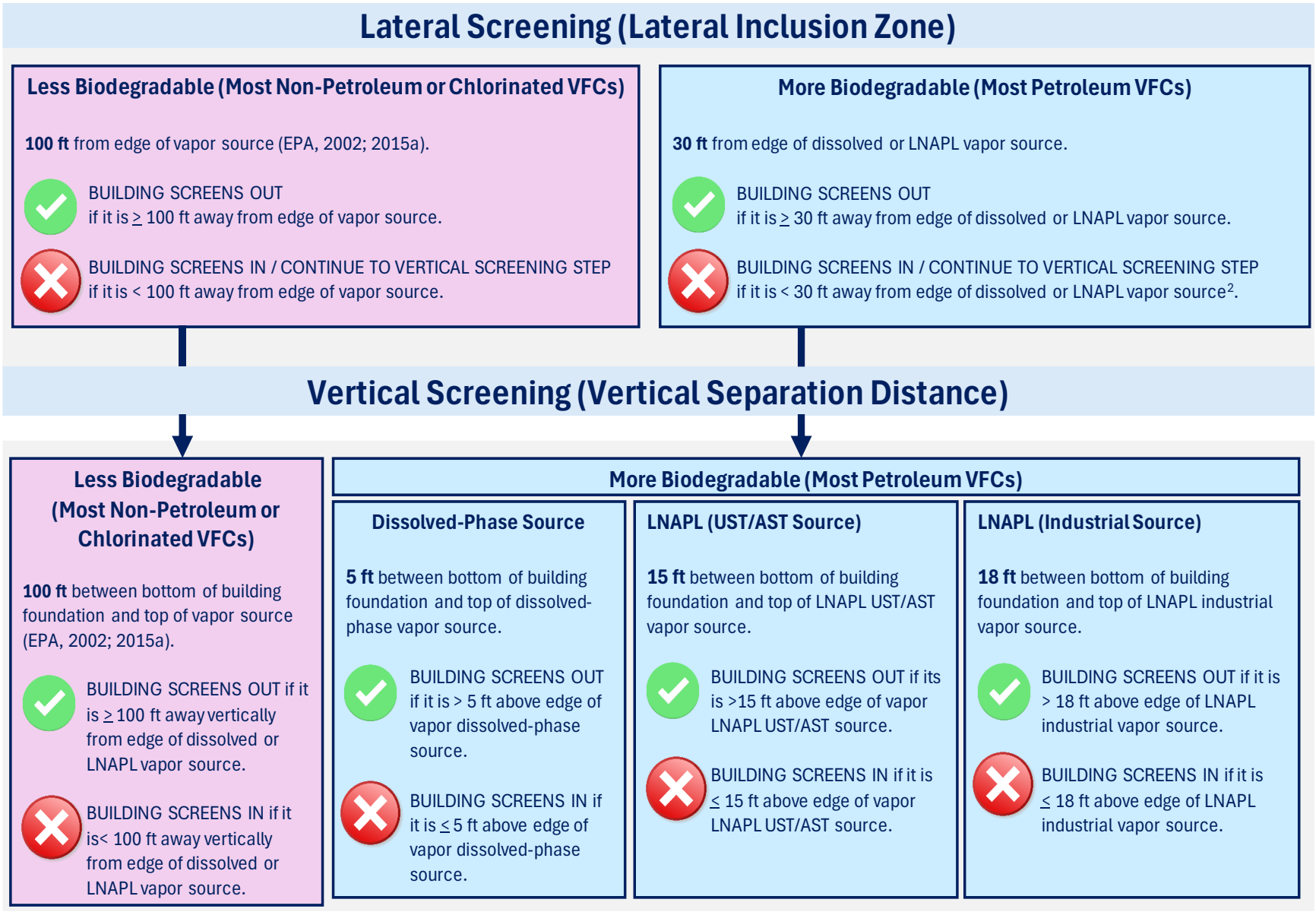
The precluding factor assessment is intended to address uncertainties in VFC migration in soil and groundwater, physical transport (advection and diffusion), and petroleum VFC biodegradation. If any of these precluding factors are present, a building cannot be screened out. The technical basis for and latest science on precluding factors for distance-based screening is presented in **Appendix E: Application of Precluding Factors**. Sites where the VI CSM is sufficiently complete for VI screening (i.e., the minimum data needs for VI screening are met) and no precluding factors are present are then subject to distance-based screening according to the method described in **Section 5.3.2**.

5.3.2. Distance-Based Screening

The goal of distance-based screening is to determine whether VFCs can migrate from a vapor source in soil or groundwater to a current or future building. Buildings located sufficiently far from a VFC source in soil or groundwater (i.e., beyond the lateral or vertical screening distances noted in **Section 5.3.2.1**) will not represent a VI risk and will require no additional VI assessment. Application of the method requires knowledge of the location of VFC vapor sources in the subsurface and the location and depth of current or future building foundations. The lateral and vertical screening distances are measured from the outermost and uppermost edges of a VFC source in soil or groundwater (e.g., exceedances of maximum contaminant levels, detection levels, or VI screening levels for specific VFCs as defined by the applicable regulatory agency) to the nearest lateral or vertical edge of the building foundation or property. VI screening levels generally serve as the basis for defining the lateral and vertical edges of a VFC source (e.g., dissolved phase or NAPL) in soil or groundwater. Maximum contaminant levels may be useful in cases where they are similar to VI screening levels. Detection levels may be useful in cases where the VI screening levels are below analytical detection levels. Uncertainties are also associated with defining the exact lateral and vertical edge of the VFC source in soil or groundwater. More information related to delineation at PVI sites can be found in **Appendix F: Distance-Based Screening at Petroleum Vapor Intrusion Sites**.

Distance-based screening is conducted sequentially, starting with lateral then vertical screening as shown in **Figure 5-2** and as described below:

- Lateral screening determines whether current or future buildings or occupied buildings are located laterally close enough to a VFC source in soil or groundwater (i.e., within the lateral screening distance or lateral inclusion zone) to pose a potential VI risk. Buildings separated from the VFC by distances less than the lateral screening distance (i.e., are within the lateral inclusion zone) require further screening based on vertical separation distance. Buildings located beyond the lateral inclusion zone do not pose a VI risk and require no further VI assessment.
- Vertical screening determines whether current or future buildings or occupied buildings are located close enough vertically to a VFC source in soil or groundwater (i.e., within the vertical screening distance) to pose a potential VI risk. Buildings separated from the VFC by distances less than the vertical screening distance require further screening based on the methods described in **Section 5.4** Step 3–Refined Vapor Intrusion Screening. Buildings located beyond the vertical screening distance do not pose a VI risk and require no further VI assessment.



Notes: 1. Distance-based screening is part of the initial VI screening (Step 2). Distance-based screening criteria are based on Interstate Technology & Regulatory Council and U.S. Environmental Protection Agency guidance and may not reflect state-specific screening distances. 2. Vertical screening may not be required at sites where the lateral edge of the dissolved or LNAPL vapor source in the subsurface can be confidently documented. Acronyms: AST = aboveground storage tank, ft = feet, LNAPL = light nonaqueous-phase liquid, VFC = vapor-forming chemical, UST = underground storage tank

Figure 5-2. Decision tree associated with implementation of distance-based screening criteria.

Sources: USEPA (2002c; 2015a).

5.3.2.1. Application of Distance-Based Screening

Lateral and vertical screening distances vary depending on whether the VFC is less biodegradable (e.g., most chlorinated hydrocarbons and mercury) or more biodegradable (e.g., most PHCs) in the vadose zone). Less biodegradable VFCs require longer source-separation distances for vapor concentrations to attenuate below a level of concern (e.g., VI soil-gas or sub-slab screening levels) by diffusion through the vadose zone than more biodegradable VFCs. USEPA (2015a) recommends lateral and vertical screening distances of 100 feet (30 m) for nonpetroleum VFCs (e.g., chlorinated hydrocarbons and mercury). These distances are based on theoretical calculations by Lowell and Eklund (2024b)and generally supported by transport modeling (Wang et al. 2020; Yao et al. 2015) and field experience (Folkes et al. 2009). The lateral screening distance for biodegradable VFCs (or lateral inclusion zone) is 30 feet. The vertical screening distances recommended by ITRC for more biodegradable VFCs, for example, generally most PHCs including TPH, TPH fractions, hexane, and naphthalene (Lahvis 2018) are listed below:

- 15 feet (4.5 m) from the top of a residual LNAPL source in soil or groundwater at a petroleum UST or AST site
- 18 feet (5.5 m) from the top of a residual LNAPL source in soil or groundwater at a petroleum industrial site
- 5 feet (1.5 m) from the estimated maximum water-table elevation for a dissolved-phase VFC source in groundwater

The type of VFC source (e.g., dissolved phase or LNAPL) and its extent in the subsurface is important for applying screening distances at PVI sites. The screening distances defined for LNAPL apply to residual-phase LNAPL, which does not appear in monitoring wells and can be challenging to identify. General indicators of residual-phase LNAPL are provided in **Appendix F: Distance-Based Screening at Petroleum Vapor Intrusion Sites** to help with identification. Of note, USEPA (2015b) recommends a vertical screening distance of 6 feet (2 m) for dissolved-phase VFC sources and no vertical screening distance for petroleum industrial sites because their VI guidance only applies to petroleum UST sites.

The vertical screening distances for biodegradable VFCs are largely based on empirical studies by USEPA (2013) and Lahvis et al. (2013).

ITRC recommends that the vertical screening distances apply to all current or future buildings located within a 30-ft (10-m) buffer distance of the edge of the delineated VFC source in soil or groundwater (as described in **Section 5.3.2**). This buffer distance is based on uncertainties in defining the exact edge of a petroleum VFC source in soil or groundwater due to the general tens of feet (several meters) of spacing of soil borings and groundwater wells during routine site investigations. The buffer distance is likely to be conservative for biodegradable VFCs given that VFCs will tend to migrate vertically upward by diffusion based on predominant VFC concentration gradients and biodegradation generally occurs at similar rates with increasing lateral and vertical VFC source-separation distance. Vertical screening distances for biodegradable VFCs should thus apply laterally provided the lateral edge of the VFC source in soil or groundwater is clearly defined (Michigan EGLE 2024).

5.3.2.2. Minimum Data Needs

The minimum data requirements for applying distance-based screening include the following:

- The VFC(s) present in the subsurface
- The lateral and vertical extent of VFC sources in the vadose zone and groundwater, including the presence of residual-phase LNAPL at PVI sites (see **Appendix F: Distance-Based Screening at Petroleum Vapor Intrusion Sites**)

- The minimum depth to the reasonably anticipated top of the water table for groundwater sources
- The depth to the top of the VFC source in the vadose zone for soil sources
- The depth of current and future building foundations below the land surface
- The site type, in particular for petroleum VFCs, and whether the site is a petroleum UST/AST site or petroleum industrial site

5.3.2.3. Uncertainties

There are several uncertainties when applying lateral and vertical screening distances, including the following:

- The role of preferential pathways in vapor migration in the subsurface
- The exact locations of outer or vertical edges of VFC sources in soil or groundwater that may vary by season (e.g., snow, precipitation) and long-term climate change (e.g., drought or sea-level rise)
- The inability to measure concentrations in shallow groundwater (i.e., at the water table) that are the source for VFCs at sites with groundwater sources, especially when sampling from wells with long saturated-screen intervals)
- Distances to current or future receptors (e.g., building foundation dimensions)
- At PVI sites:
    - The volume of LNAPL released at petroleum industrial sites, which can affect the selection of a 15-ft (4.5-m) or 18-ft (5.5-m) vertical screening distance for LNAPL sources
    - The effect of future building construction on oxygen availability and aerobic biodegradation in the subsurface at PVI sites

It is also important to note that there are uncertainties inherent within the empirical databases used to derive screening distances (i.e., knowledge of the top of LNAPL sources above the water table). Professional judgment can always be used to adjust screening distances at some sites where spatial and/or temporal variabilities are significant.

5.4. Step 3–Refined Vapor Intrusion Screening

Refined VI screening uses concentration-based methods (Section 5.4.1) or mass-flux-based methods (Section 5.4.2) to further screen buildings that do not screen out based on the preliminary VI exposure assessment or initial VI screening. Refined VI screening involves either concentration-based screening or mass-flux-based screening (or both) that are chosen based on relevance, data availability/data collection needs, and urgency of VI screening decision. In general, more site-specific data are required to support concentration-based screening than mass-flux-based screening.

5.4.1. Concentration-Based Screening

Concentration-based screening involves a comparison of measured VFC concentrations (e.g., groundwater, subsurface vapor, or indoor air) to media-specific default or generic (Tier 1) or site-specific (Tier 2) VI screening levels that are underpinned by a scientifically sound VI CSM. Concentration-based screening is generally iterative beginning with the screening of groundwater or vadose-zone soil vapor between the source and building followed by the screening of sub-slab soil vapor and, lastly, indoor air. Provided the measured vapor VFC concentrations are below and predicted to remain below the VI

screening levels, the building can be screened out without the need for additional VI assessment. If generic VI screening levels are exceeded, one or more of the following actions can be taken:

- Further default or site-specific concentration-based screening using alternative media (e.g., screening soil vapor if groundwater was used in the initial screen or indoor air if sub-slab soil vapor was used in the initial screen)
- Further VI screening using mass-flux-based screening (**Section 5.4.2**)
- VI mitigation (see **Chapter 10: Vapor Intrusion Mitigation** and associated fact sheets)
- Remediation of the VFC source (**Chapter 10: Vapor Intrusion Mitigation**)

The preferred media (e.g., groundwater, subsurface vapor, or indoor air) for VI screening may differ depending on the VI scenario and local regulatory requirements. Some regulatory agencies may require sampling of indoor air for screening purposes at sites where (1) high concentrations of VFCs are detected in shallow soil or groundwater and (2) preferential VFC vapor migration via floor drains, sumps, elevator shafts, and foundation penetrations is known or suspected where comparisons between measured subsurface concentrations and risk-based screening levels based on application of a default AF are not technically defensible. There also may be instances where it is more prudent to sample VFCs in soil vapor, sub-slab soil vapor, or groundwater before entering a building and encumbering occupants or encountering background sources of VFCs in indoor air that could confound VI assessments. In such cases, the subsurface concentration measurements are used to predict concentrations in indoor air assuming a default AF (see the **Attenuation Factors Fact Sheet**) that accounts for the attenuation of VFC concentrations as vapors migrate from the subsurface to indoor air. If measured VFC concentrations are below media-specific VI screening levels, no further site assessment is typically required.

More information on default (generic) and site-specific VI screening levels and their development is provided in the **Screening Levels Fact Sheet**. Additional information on minimum data needs to support concentration-based screening is provided in **Section 5.4.1.2**.

5.4.1.1. Application of Concentration-Based Screening

Generic (Tier 1) or site-specific (Tier 2) VI screening levels are defined by the applicable regulatory agency. These screening levels can vary by up to three orders of magnitude in indoor air, up to four orders of magnitude in groundwater, and up to five orders of magnitude in soil vapor for the same VFC. The disparity in screening levels exists because of differing assumptions related to risk, VFC toxicity values, incorporation of background levels from published studies (see **Section 2.2.4** and **Background Sources to Indoor Air Fact Sheet**), chemical parameters, consideration of future buildings, and exposure factors for vapor inhalation. The VI screening levels are generally derived from a standard set of ASTM and/or USEPA equations, which factor in both cancer risks and non-cancer hazards from chronic inhalation exposure and toxicity factors defined by the applicable regulatory agency and the following assumptions:

- A constant source of VFCs in soil or groundwater beneath a building with a concrete (basement or slab-on-grade) foundation for the entire duration of inhalation exposure; and
- VFC concentrations in indoor air are well mixed and proportional to those in sub-slab soil vapor, assuming no background VFC sources in indoor or outdoor air (see **Section 2.2.4 Background Sources of Chemicals** and **Background Sources to Indoor Air Fact Sheet**).

The VI screening levels also vary depending on the extent to which VFC concentrations decrease or attenuate as VFCs migrate across building foundations. Many regulatory agencies assume VFC concentrations decrease by 33×, which equates to a default slab AF of 0.03 when specified as the reciprocal (Eklund et al. 2023). This value was recommended by USEPA (2015a) based on a USEPA (2012b) empirical study of paired TCE and PCE vapor concentration measurements made inside and

below residential buildings (primarily with basement construction) at sites located across the U.S. Additional information on screening levels and their application can be found in the **Screening Levels Fact Sheet**.

Since 2012, several empirical AF studies have been undertaken to address the applicability of USEPA's default AF for a broader range of VI site-specific conditions (e.g., nonresidential buildings, residential buildings with slab-on-grade foundations) (see the **Attenuation Factors Fact Sheet** for more information on the AF and the empirical studies. Some states (e.g., Georgia, Hawaii, Indiana, North Carolina, Oregon, and Pennsylvania) have adopted separate AFs for residential and nonresidential buildings (Eklund et al. 2023). See **Appendix A: State Practices** for more information on individual states AFs.

The USEPA generated Regional Screening Levels (USEPA 2024a) and a VISL calculator (USEPA 2024b) (see the **Vapor Intrusion Screening Level Calculator Fact Sheet**) to drive greater consistency among VI screening levels within states and the regulated community. USEPA's VI screening levels do not account for biodegradation in the vadose zone and thus will tend to be disproportionately low if applied to most petroleum VFCs. In addition, biodegradation results in depth-dependent AFs that vary as a function of VFC source-separation distance. California recommends applying a 1,000× increase (or bioattenuation factor) to default VI screening levels for benzene, ethylbenzene, and naphthalene in soil vapor collected 5 feet (1.5 m) or more from a building foundation provided conditions in the vadose zone are aerobic (i.e., oxygen concentrations in soil vapor exceed 4% vol/vol) (California Water Boards 2012). Some states also have soil-gas screening levels that trigger rapid response actions if exceeded (California DTSC 2014; NJDEP 2021).

As noted in Eklund et al. (2023), indoor air screening levels for certain VFCs may be below background level concentrations documented in residential buildings across North America (Dawson and McAlary 2009; Rago et al. 2021; USEPA 2011a). Such low screening levels can complicate concentration-based screening. Concentration-based screening can be further complicated by VI screening levels that may not exist for certain VFCs. The number of VFCs with published VI screening levels in U.S. guidance varies from less than 10 to several hundred (Eklund et al. 2024). Lastly, some states have established subsurface screening levels that require rapid response actions if exceeded (California DTSC 2014; NJDEP 2021).

Lastly, VI screening levels may not be applicable at certain operating facilities and industries where indoor air is regulated by the Occupational Safety and Health Administration (OSHA). Such cases typically involve chemicals that are routinely used and handled during facility operations, including the following types of situations:

1. Workers are commonly exposed to the chemical as part of their normal work activities.
2. The chemical is routinely used in a manufacturing or commercial process and not from the subsurface.
3. Workers are informed of the potential hazards of working with the chemicals.
4. Workers volunteer to accept potential exposure.
5. The business monitors and prevents worker exposures.
6. Workers are medically monitored (annually) to assess potential exposure.

VI screening levels will still apply to individuals at such facilities who are not aware of potential VFC exposures (e.g., office staff and visitors).

5.4.1.2. Minimum Data Needs

Concentration-based screening typically includes sampling in the following order:

1. Sampling the VFC source in soil or groundwater
2. Sampling the VFC pathway (vadose-zone soil vapor between the source and receptor)
3. Sampling adjacent to and inside the building (sub-slab soil vapor and indoor air)

Soil vapor sampling can be a preferred medium for concentration-based screening because of the following factors:

- Higher probability of encountering background sources of the same VFCs in indoor air and sub-slab soil vapor (Dawson and McAlary 2009; McHugh et al. 2006; Rago et al. 2021)
- Potential for poor correlation of VFC concentrations in groundwater with those in soil vapor or indoor air (Lahvis et al. 2013)
- Generally higher spatial and temporal variability of VFC concentrations in sub-slab soil vapor versus near-slab soil vapor for VFC sources in relatively deep soil or groundwater (Luo et al. 2009)

If emergency and rapid response conditions are present or relatively high VFC sources are located in relatively close proximity (e.g., < 3 feet or 1 m) to building foundations, vapor collection should initially target the VFC building receptor and indoor air. Indoor air should also be targeted for concentration-based screening when a known or suspected preferential pathway (e.g., elevator shafts, sumps, open floor drains, foundation penetrations and large cracks, etc.) exists that causes VFC vapors to circumvent migration across building foundations. For a future building or redevelopment scenario, the VFC source and pathway should be initially targeted. In general, future scenarios are screened using soil vapor data or alternative screening methods such as distance-based screening (**Section 5.3.2**) or mass-flux-based screening involving vapor transport modeling (see **Section 5.4.2** and **Chapter 9: Modeling**).

Other data needs to apply concentration-based screening include information on the following factors:

- The lateral and vertical extent of VFC sources in the vadose zone and groundwater
- Preferential pathways and conduits for vapor migration (e.g., bedrock, foundation footings, sewer laterals, and utility conduits) that directly connect the VFC source in soil or groundwater to the building foundation
- Current and future building foundation types (e.g., concrete or crawl space)
- The relative depth and distribution of VFC sources and concentrations in the subsurface
- General hydrogeologic conditions in the vadose zone (e.g., presence of perched water, soil types and thicknesses, preferential pathways for vapor migration)

5.4.1.3. Uncertainties

Concentration-based screening incorporates conservative assumptions designed to account for uncertainties in VI exposures attributed to the following factors:

- High spatiotemporal variability in VFC concentrations in sub-slab soil vapor and indoor air, which can range over three orders of magnitude (Bekele et al. 2014, 20; Folkes et al. 2009; Holton et al. 2013; Luo et al. 2009)

- Vapor migration through the vadose zone and across building foundations
- A high likelihood of encountering background sources of VFCs in indoor air (Dawson and McAlary 2009; Rago et al. 2021; USEPA 2011a)
- Inhalation exposure parameters and toxicity factors, especially when cumulative risks from multiple VFCs are considered
- The magnitude of the slab AF
- The building ventilation rate (HVAC operation)
- Meteorological conditions (e.g., precipitation events, barometric pressure changes)
- Climate change
- VFC source attenuation (weathering)
- Airflow and leakage rates (air exchange) inside buildings, within crawl spaces and below building and occupied building foundations (Reichman, Roghani, et al. 2017; Reichman, Shirazi, et al. 2017)

At PVI sites, vapor concentrations in the vadose zone will also be highly variable. Vapor concentrations will tend to: (1) decrease significantly with increasing distance above a VFC source when conditions in the vadose zone become favorable for aerobic biodegradation (USEPA 2015a; USEPA OUST 2015) and (2) vary significantly above LNAPL sources in response to fluctuating water-table conditions and the submergence of residual-phase LNAPL in the smear zone. Vapor sampling during high and low water-table events can be used to reduce or bound the uncertainty.

Collectively, uncertainties with concentration-based screening are greater than those associated with distance-based screening. It is not uncommon for concentration-based screening to result in extensive and prolonged data collection (see **Chapter 8: Data Evaluation and Vapor Intrusion Risk Assessment**). In such scenarios practitioners must decide whether to continue to conduct VI screening or transition to further VI screening using the mass-flux method (**Section 5.4.2**), VI mitigation (see **Chapter 10: Vapor Intrusion Mitigation** and associated fact sheets), or VFC source (**Chapter 10: Vapor Intrusion Mitigation**). Lastly, it is important to emphasize that VI screening levels are meant to be conservative and bound uncertainties in VI exposures associated with spatiotemporal variabilities that cannot be fully documented.

5.4.2. Mass-Flux-Based Screening

Mass flux is defined as the rate of chemical mass flow through a unit area per unit time. In the context of VI, the mass flux defines the rate of VFC migration (1) through a vadose zone (generally by diffusion and biodegradation), (2) near and across a building foundation (generally by diffusion and advection), and (3) inside and out of a building (generally by advection). Additional VI assessment is not required provided the mass flux of VFCs to indoor air is sufficiently small to prevent VFC concentrations from exceeding indoor air screening levels. Methods for mass flux-based screening include (1) vapor transport modeling to predict VFC concentrations in indoor air based on VFC concentrations measured in soil-gas (either from single or nested soil-gas probes) (**Figure 5-3A**), (2) measurements of VFC mass discharge (Q_{BPC}) across a blower door during indoor air depressurization (also referred to as BPC) (**Figure 5-3B**), and (3) measurements of VFC mass discharge during sub-slab soil vapor depressurization (Q_{SSG}) (**Figure 5-3C**). A related term is mass discharge, which defines the volumetric airflow of soil vapor from the subsurface to indoor air (Q_{soil}) and within and out of a building ($Q_{building}$). Mass discharge is expressed in terms of volume per unit time. Mass flux and mass discharge can be used in exposure assessments, remedy design, compliance, performance monitoring, and optimization.

The application of mass-flux screening is inherent to all VI transport models and spreadsheet tools underpinned by conservation of mass principles (e.g., Johnson and Ettinger 1991), BioVapor (e.g., API 2012a), PVIScreen (USEPA 2018), and PVI-2D (Yao et al. 2017) (see Chapter 9: Modeling). These models and tools are used to predict relatively long-term exposures to concentrations of VFCs in indoor air and derive risk-based screening levels assuming VFC transport from the subsurface to indoor air is in a pseudo-steady state; this means the VI models and tools do not account for short-term variabilities and exposures associated with meteorological events (Kram and Solgi 2025). The uncertainty with model predictions and estimates is accounted for by the application of conservative transport assumptions (soil and building properties) and, in certain cases, model sensitivity analyses.

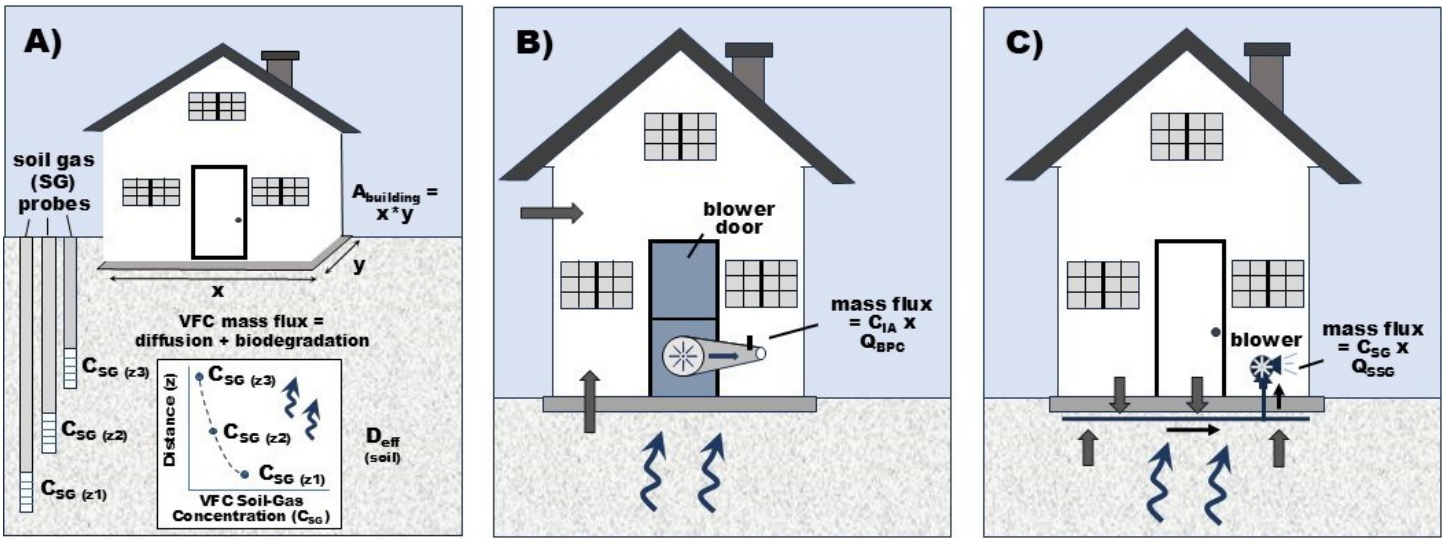


Figure 5-3. Conceptualization of various mass-flux-based screening methods involving (A) analyses of depth-discrete concentrations ($C_{SG\ (z1–z3)}$) of vapor-forming chemicals (VFCs) in soil vapor using vapor transport modeling and a default or building-specific estimate of the effective diffusion coefficient of vadose-zone soil (D_{eff}), (B) measurements of VFC concentrations in indoor air (C_{IA}) and airflow rates across a blower door associated with indoor air depressurization (e.g., building pressure cycling - Q_{BPC}), or (C) measurements of VFC concentrations and airflow rates associated with sub-slab soil vapor depressurization (Q_{SSG}).

Source: Adapted from ESTCP (2025).

Alternatively, temporal variability and other uncertainties associated with estimating concentrations of VFCs in indoor air (e.g., contributions from background sources—see Section 2.2.4 and Background Sources to Indoor Air Fact Sheet) may be avoided using depressurization methods for mass-flux-based screening. These methods can provide an estimate of the greatest potential VI exposure and can be used to obtain site-specific AFs and sub-slab soil-gas screening levels (ESTCP 2025; McAlary, Wertz, et al. 2018). The challenge with depressurization methods is that they require relatively sophisticated tools, equipment, and experienced personnel to apply. Application of depressurization methods for site screening purposes has also not been reported in the literature even though such methods are increasingly being applied in VI risk assessment. Mass-flux depressurization methods can also be used to support mitigation design and performance evaluations (see Section 7.7.2 and the Pressure Monitoring and Building Pressure Control Fact Sheet).

5.4.2.1. Application of Mass-Flux-Based Screening

5.4.2.1.1. Modeling

The application of mass-flux-based screening using various VI models and spreadsheet tools (Hers et al. 2002; Yao, Shen, Pennell, et al. 2013a) is well established (see **Chapter 9: Modeling**). These models are either used to predict the VI risk in current or future buildings or develop VI screening levels by simulating the steady-state mass flux of VFC vapors in the vadose zone, across building foundations, and within indoor air. These VI models, along with others used to simulate VFC vapor migration (Hers et al. 2002; Yao, Shen, Pennell, et al. 2013a), provide estimates of VFC mass flux based generally on measured VFC concentrations in soil vapor or groundwater and default or site-specific soil properties and building properties. Mass-flux estimates are then used to estimate VFC concentrations in indoor air based on assuming a default building air exchange rate (see **General Concepts of Mass-Flux-Based Screening Fact Sheet**). The concentrations of VFCs in soil vapor used as model input can be either point measurements or vertical profiles as indicated in **Figure 5-3A**. Mass-flux estimates derived from vertical soil-gas profiles are obtained by a best fit of model-predicted and measured VFC concentrations. The models assume that VFC source concentrations remain constant and that VFC concentrations in indoor air are well mixed. VI models are often the only tool available for VI screening at buildings where VFC sampling in indoor air is not possible (i.e., buildings planned for future construction or redevelopment). For most other VI screening applications, additional MLE (e.g., soil vapor or indoor air samples) are required for model validation before a building can be screened out from further VI assessment. Modeling is also recommended over depressurization methods for mass-flux-based screening (**Figure 5-3B** and **Figure 5-3C**) at large nonresidential buildings where complete capture of the airflow or inside or below the foundation is difficult to obtain. Additional information regarding mass-flux and VI modeling are provided in **General Concepts of Mass-Flux-Based Screening Fact Sheet**, **Chapter 9: Modeling**, and **Flux Chamber and Other Flux Measurement Devices Fact Sheet**.

5.4.2.1.2. Depressurization Methods

The use of depressurization technologies to obtain VFC mass-flux estimates is documented by USEPA (2012b), the Environmental Security Technology Certification Program (ESTCP) (ESTCP 2025; McAlary, Wertz, et al. 2018) and the U.S. Navy (NFESCA 2021). VFC mass-flux estimates are obtained from measurements of VFC concentrations and airflow rates across blower doors associated with the depressurization of indoor air or subsurface vapor, respectively (Beckley et al. 2014; ESTCP 2025, 205; Lutes et al. 2019; McAlary, Gallinatti, et al. 2018; McAlary, Wertz, et al. 2018; McHugh et al. 2012; Nicholson et al. 2021) (see **Figure 5-3B** and **Figure 5-3C**). Such technologies are increasingly being used to: (1) estimate relatively worst-case VFC concentrations in indoor air, (2) derive building-specific AFs (i.e., sub-slab soil-gas screening levels), and (3) optimize the design of VIMS. The mass-flux can provide a more complete measure and upper-bound estimate of the potential impact to a [building] receptor, be applied with limited site data, and have equal or less uncertainty than concentration-based methods. Actual documentation of depressurization technologies for screening purposes has not, however, been reported in the literature to date. The methods can be relatively intricate and challenging to implement, and only experienced and highly qualified persons should be relied upon for execution. To help with this, protocols and case studies involving their use in VI risk assessment continue to be developed (Beckley et al. 2014; ESTCP 2025; Lutes et al. 2019; McAlary, Wertz, et al. 2018) (ESTCP 2025). Practitioners are thus encouraged to consult with the local regulatory authority for approval prior to execution.

5.4.2.2. Minimum Data Needs

5.4.2.2.1. Modeling

The use of vapor transport modeling in VI site screening requires the development of a CSM that includes, at a minimum, an understanding of subsurface sources (e.g., lateral and vertical extent and VFC

concentrations in soil and groundwater), pathways (e.g., presence of preferential pathways for vapor migration in the subsurface and across building or occupied building foundations, VFC concentrations in soil vapor between the source and building or occupied building foundation, and general hydrogeologic characteristics of the vadose zone, such as soil types and thicknesses and presence of perched water), and receptors (e.g., current and future building types, foundation types and depth, locations, and land use). VI sites with complex CSMs where the vapor source is not located directly below the current or future building may necessitate more sophisticated numerical modeling. Such model applications generally involve extensive site characterization and fall outside of site screening. Physical parameter ranges and values for variables commonly used in VI modeling are reported in USEPA (2004), API (2012), and USEPA (2016). Ranges of aerobic biodegradation rates for petroleum VFCs can be found in DeVaull et al. (1997), DeVaull (2011), and the **BioVapor Model Fact Sheet**. Additional information on data needs for VI transport modeling is provided in **Chapter 9: Modeling**.

5.4.2.2.2. Depressurization Technologies

Minimum data needs for the application of indoor air and SSD technologies are relatively few compared to the other screening methods, and generally include the following:

- Foundation type (e.g., basement, slab-on-grade, crawl space)
- Vapor monitoring and pressure measurements inside and below building foundations
- Airflows and VFC concentrations associated with off-gas emissions
- Presence and location of potential pathways and conduits (e.g., elevator shafts, sumps, open floor drains, sewer laterals, foundation penetrations and large cracks, etc.) for vapor migration across the building or occupied building foundation

SSD technologies can also include tracer testing and mathematical modeling (ESTCP 2025; McAlary, Wertz, et al. 2018). For this reason, it is important to review the benefits and challenges of depressurization-based methods for site screening upfront in the screening process (i.e., during screening data evaluation).

5.4.2.3. Uncertainties

5.4.2.3.1. Modeling

Uncertainties associated with the application of VI models for mass-flux-based screening include those associated with the inability to accurately simulate the following:

- Key vapor transport processes in the vadose zone, across building foundations, within crawl spaces and indoor air, including the following:
  - Diffusion through concrete foundations (Kobayashi and Shuttoh 1991; Patterson and Davis 2009; Tittarelli 2009)
  - Effective diffusion coefficients of vadose-zone soils
  - Fluctuating gaseous-phase advection in shallow soil vapor caused by variations in differential pressures across building foundations (Lundegard et al. 2008; McHugh et al. 2006; Patterson and Davis 2009; Robinson et al. 1997)
  - Biodegradation in the vadose-zone and gaseous-phase advection associated with methane generation (Jewell and Wilson 2011; Ma et al. 2014; Sihota et al. 2013; Wilson et al. 2012; 2013)
  - Air exchange and leakage within indoor air and crawl spaces (Reichman, Roghani, et al. 2017; Reichman, Shirazi, et al. 2017)

- Spatiotemporal variability in VFC concentrations, model processes, and parameter values (e.g., crack factors, diffusion coefficients, pressure differentials, soil porosities)
- Background sources in indoor air (see **Section 2.2.4 Background Sources of Chemicals** and **Background Sources to Indoor Air Fact Sheet**)
- Potential vapor migration via preferential pathways
- VFC source attenuation (i.e., decrease in source vapor concentrations associated with weathering) over the duration of the VI exposure or changes in VFC source concentrations in response to seasonality or longer-term climate change

The uncertainty in vapor transport modeling is largely offset by either the application of conservative parameter values that bound a range of anticipated site conditions or the implementation of uncertainty and sensitivity analyses (see **Chapter 9: Modeling**).

5.4.2.3.2. Depressurization Methods

Uncertainties associated with the application of depressurization systems include the following:

- The inability of the venting system to adequately entrain air inside or below the building or occupied building
- Variable and preferential airflow within, around, and below buildings
- Spatiotemporal variability in current or future VFC concentrations (associated with seasonality or climate change)
- Temporal variability in airflow rates (gas flows: Q_{BPC} and Q_{SSG})

5.5. Vapor Intrusion Screening Outcomes

If the screening process indicates potential VI risks exist for a building, the site is now screened in and should move to one of the following next stages:

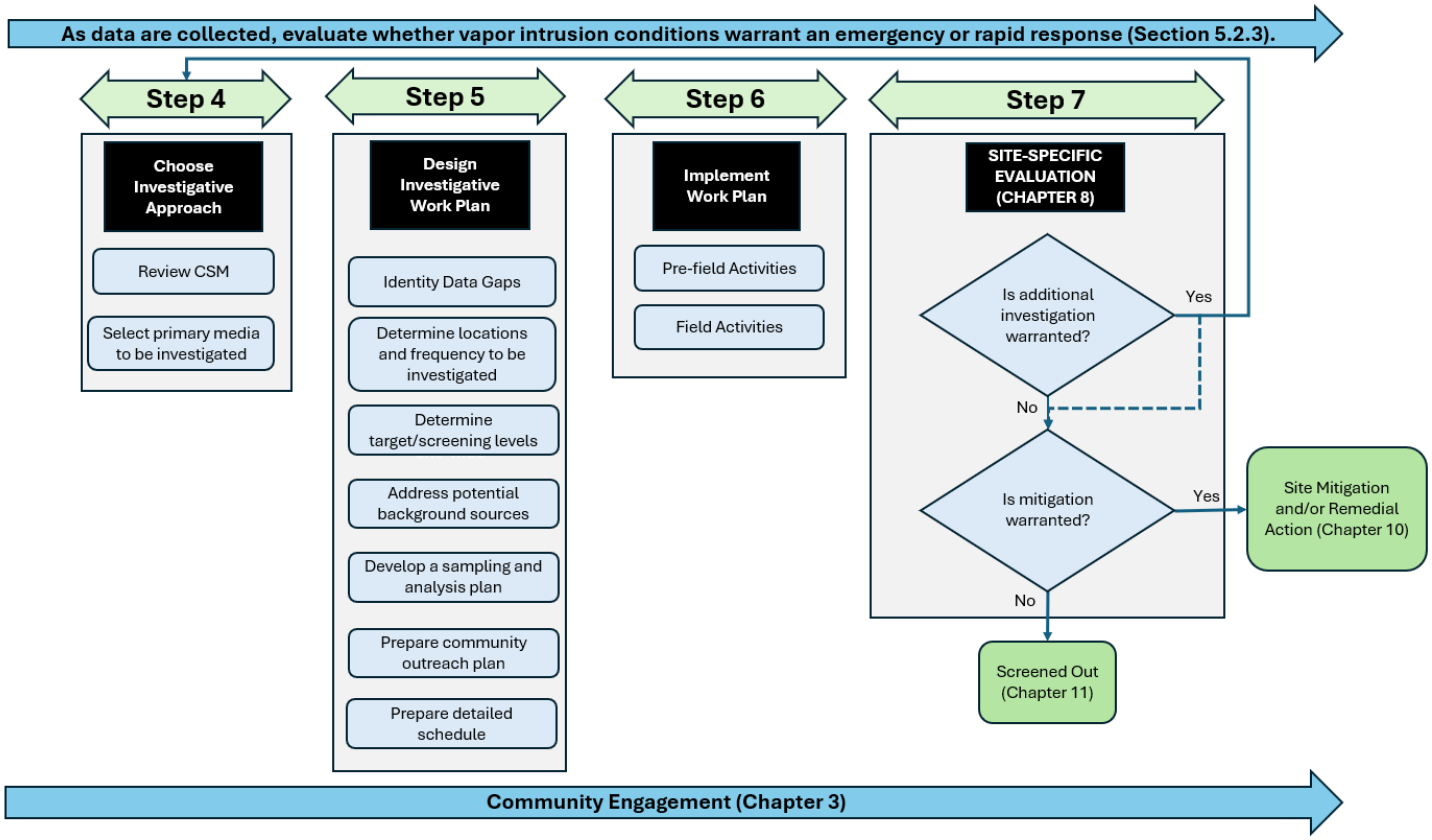
- Iterative site investigation (**Chapter 6: Iterative Investigation Process**)
- Site-specific evaluation (**Chapter 8: Data Evaluation and Vapor Intrusion Risk Assessment**)
- Remedial action (**Chapter 10: Vapor Intrusion Mitigation**)
- Mitigation (**Chapter 10: Vapor Intrusion Mitigation**)

If the screening process does not indicate potential VI risks exist for a building (i.e., it is screened out), no further VI evaluation is necessary (**Chapter 11: Vapor Intrusion Component Determination, Exit Points, and Closure**). It is imperative that the CSM be sufficiently complete (i.e., the CSM contains the minimum data needed) to perform site screening.

CHAPTER 6: ITERATIVE INVESTIGATION PROCESS

> ***Sampling Techniques and Analytical Methods***
>
> Chapter 7 presents various sampling and analysis methodologies available for VI investigations. The information in that chapter will help you select the sampling techniques and analytical methods that will best meet the data objectives for targeted media (i.e., soil vapor, sub-slab vapor, and air). The most common sampling locations and sampling media for a VI investigation are shown on Figure 7-1.

Investigating the VI pathway can often be iterative and intertwined with the screening process, as an investigation can occur at any point in a project's life stage when a data gap is identified. The type of investigation warranted to address the identified data gap can vary from a desktop study to collecting data in the field, which may include sampling inside buildings. For example, to screen a site and/or building, there is minimum data needed to apply a screening method, and the practitioner may be able to gather the necessary data via desktop methods; however, if the data are not available, the practitioner will need to collect additional data in the field. As another example, if a site and/or building fails to be eliminated by the screening process, the practitioner will need to collect additional data in the field to further evaluate the potential current and future VI risk at the building. The various aspects of VI investigations are more commonly integrated into the screening process due to the iterative nature of evaluating the risk to human health from a potential VI pathway. It should be noted, however, that some states consider screening and investigation as separate unique phases, and while the division between the screening and investigation processes is not typically clear, most regulatory agencies recognize the need for some level of initial information/data to support the need for additional investigatory, mitigatory, and/or remedial actions. The following sections in this chapter describe the stepwise investigation process, shown in Figure 6-1, for choosing an investigation approach, designing the investigation work plan, implementing the work plan, and evaluating the site-specific data to determine appropriate next steps.



Note: CSM = conceptual site model.

Figure 6-1. Generalization of iterative investigation process.

6.1. Step 1–Choose Investigative Approach

Before conducting an additional VI investigation, the practitioner must first decide on the appropriate investigation approach (i.e., the information needed for addressing the data gaps). This approach should generally be guided by the CSM characterization stage (see **Section 4.2**) and the site-specific DQOs (see the **Data Quality and Adequacy Fact Sheet**). These distinctive investigation approaches are typically initiated in a progressive or phased manner, generally starting with subsurface investigation. The need for additional investigations may occur after each period of data collection when the CSM is updated (**Chapter 4: Conceptual Site Model**). Different sampling methods (**Chapter 7: Sampling and Analysis**) are available based on the environmental medium and VFCs being investigated.

The same approaches that are used to investigate VFC sources that may aerobically degrade (such as those for PVI and vinyl chloride) are often the exact same that can be used for those that do not. When evaluating VFCs that biodegrade, there should be a greater emphasis on collecting additional field parameters, such as O_2, CO_2, and CH_4, to identify the active zone of biodegradation. **Chapter 7: Sampling and Analysis** describes different tools and methods that can be used to investigate aerobically degradable hydrocarbons.

Details on the sampling methodologies for each medium, including advantages and disadvantages, are discussed in **Chapter 7: Sampling and Analysis**. It is common to use multiple methods during an investigation as each may provide additional MLE (see the **Multiple Lines of Evidence Fact Sheet**). For example, it may be beneficial to collect interior samples (e.g., sub-slab vapor or indoor air) in conjunction with exterior samples (e.g., soil vapor) when investigating a site with both known and unknown potential sources.

Table 6-1 summarizes typical environmental media that are considered for VI assessments. In some cases, the site CSM may suggest other media as important contributors to VI. For example, impacted vapor inside sewer lines could contribute to VI at a site using conduits as a preferential pathway (see **Vapor Intrusion Preferential Pathways Fact Sheet**). In those instances, conduit vapor or liquid sampling can be used as an investigation approach (see **Section 7.6.4 Sewer and Other Utility Conduits**). As indicated in **Table 6-1**, each investigative approach in an environmental medium has uncertainties as it relates to the VI pathway, resulting in the potential for false positives (due to conservative assumptions) or the risk of false negatives (if less conservative assumptions are used).

Prior to selecting the appropriate investigation approach, the proximity of an existing or planned future building to the VFC source should be considered using the lateral-separation screening method (see **Section 5.3.2**) to determine which areas need to be incorporated into the development of the investigation approach (see "1" on **Figure 6-2**).

The VI pathway investigation approach often begins in the subsurface exterior to the existing building or near a planned future building, starting with the collection of groundwater and/or soil vapor samples (see "2" on **Figure 6-2**). Some states (i.e., Massachusetts) may begin the investigation approach of a VI assessment by collecting qualitative indoor air grab samples (USEPA 2015a) prior to collecting subsurface samples. While grab samples may provide a yes or no answer to the presence of VFCs in indoor air and/or potentially identify a preferential pathway, the data are not quantitative and cannot be used to rule out a VI pathway or support a VI risk assessment. The investigation approach for collecting these samples will depend on the key components described in the work plan sections of this chapter. For example, shallow groundwater may prevent the collection of soil vapor samples, which can more accurately identify the concentrations of vapors beneath the building and may require direct volatilization to the indoor air pathway to be evaluated (see the **Direct Volatilization to Indoor Air Fact Sheet**). Many practitioners and state agencies use subsurface investigative approaches to evaluate the VI pathway completeness and VI risk prior to testing the air inside a building unless rapid response is required.

Table 6-1. Investigation medium overview and considerations.

Environmental Medium to be Investigated	Investigation Approach	Principal Issue(s)
Groundwater	Commonly used when a vapor source is present in the shallow portion of the aquifer. The modeling is typically conservative as it requires an estimate of indoor air concentration based on how a VFC will volatilize into the unsaturated pore space, diffuse through the soil column, and then enter into a building.	Groundwater is a relatively weak predictor of vapor intrusion exposure in indoor air (Levy et al. 2023; Yao, Shen, Pennell, et al. 2013c). Imprecision of attenuation factors or modeling typically requires conservative assumptions.
Soil Vapor	Commonly used when a vapor source is present within the unsaturated zone or to evaluate the migration of vapors through the soil column that may enter into a building. For migrating groundwater plumes, it may be beneficial to collect paired deep and shallow soil vapor samples to measure the attenuation between those two points.	Fewer pathway assumptions are required than groundwater, but the accuracy and representativeness of measurements may be an issue.
Sub-Slab Vapor	Commonly used to collect vapors immediately beneath a building. Though typically less conservative than soil vapor or groundwater, the farther away (laterally or vertically) a building is from the source of the vapor-forming chemical, the more conservative the estimate may be.	Fewest pathway assumptions required, but intrusive and attenuation factors may still be conservative for many buildings.
Indoor Air	Indoor air concentrations directly measured within a building that can be directly compared to health-based screening values.	Indoor air sampling may be intrusive to building occupants, and background sources may confound data interpretation. Concentrations may also be highly variable due to seasonal variations, human activity, and ventilation dynamics.

This approach can provide you with sufficient subsurface data to use a generic or site-specific AF to predict indoor air concentrations to use in a refined screening method as MLE for an existing or planned future building. This LOE is useful in determining whether further sampling is needed and if so, to identify appropriate sampling locations/buildings. It should be noted that the AF presumes a directly proportional relationship between the subsurface concentration and indoor air concentration, which may not be the actual relationship at the building (Hallberg et al. 2021; Levy et al. 2023; Yao, Shen, Pennell, et al. 2013b). Therefore, practitioners should consult their appropriate regulatory agency to determine whether this LOE may be used to determine site management decisions (e.g., mitigation) for a project. This approach also results in less inconvenience to building occupants and avoids the complexities of potential background sources of VFCs (see the **Background Sources to Indoor Air Fact Sheet**).

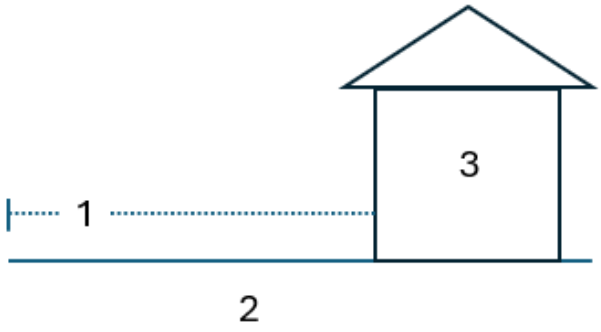


Figure 6-2. General progressive or phased investigation approach.

If additional investigation is needed to determine whether or not the pathway is complete at a specific building, the next investigation approach should expand to media inside the building (see "3"

on Figure 6-2), such as collecting sub-slab vapor, indoor air, outdoor air, and/or additional soil vapor samples. Practitioners may also consider assessing potential preferential pathways (see the Vapor Intrusion Preferential Pathways Fact Sheet). The sections below present the key components of a work plan that would address these various investigation approaches for collecting these samples. Many practitioners and state agencies use subsurface and indoor air investigative approaches to evaluate the VI pathway completeness and VI risk prior to remediation, mitigation, or other risk management decisions unless rapid response is required. This approach can also provide sufficient data to derive a site-specific AF to confirm model predictions of indoor air concentrations or use for future investigations and risk management decisions. See Section 8.5.3 and the Attenuation Factors Fact Sheet for additional information.

6.2. Step 2–Design the Investigation Work Plan

Once the investigative approach is selected (or established by state policy/guidance), a work plan is developed to further assess the VI pathway. Key components of any VI investigation work plan may include the following:

- Updating the CSM
- Identifying data gaps and investigation goals
- Determining sample locations and frequency to be investigated
- Addressing background contaminant sources
- Developing the sampling and analysis plan
- Preparing a community relations plan
- Formulating a schedule and deliverable commitments
- Completing pre-field activities
- Completing the field investigation

Each of these elements is briefly described below.

6.2.1. Conceptual Site Model

As discussed in Chapter 4: Conceptual Site Model, any gaps or uncertainties in the CSM should be identified as data gaps and incorporated into the work plan. Identifying key questions can support what type of data is needed to address any gaps or uncertainties, such as, Is VI occurring at the targeted building? or Are there background indoor air sources influencing indoor air at the targeted building? (see the Multiple Lines of Evidence Fact Sheet). Additional guidance on developing and refining CSMs is available in Chapter 4: Conceptual Site Model.

6.2.2. Data Gaps

A basic level of information is required to evaluate the potential for VI, regardless of the investigation approach. If this information is not known to a sufficiently conservative degree, it constitutes a data gap. It should be noted that additional data gaps may emerge based on the selected investigative approach and resulting data; thus, additional investigations may be warranted.

For example, approaches that rely on modeling of groundwater concentrations require site-specific data on geology and the nature/extent of VFCs in groundwater beneath the building of concern. On the other hand, strategies that primarily rely on interior air measurements for risk management decisions may only require general information on the nature and extent of groundwater contamination to guide the sampling program.

6.2.3. Determining Sample Locations

The specific properties or buildings that require investigation should be identified in the work plan. This decision is relatively straightforward when only one property or building is involved. When multiple off-site buildings are potentially impacted, selecting the initial property or building for investigation can be more complex.

Some guidance documents (e.g., USEPA 2002c) suggest selecting the worst-case building(s)—those most likely to be impacted by VI—for the initial investigations. Identifying the worst-case building is not always straightforward due to the many factors that influence VI, such as COC concentrations in groundwater, soil vapor, depth to groundwater, soil types, building type, construction type, ventilation, and groundwater flow direction.

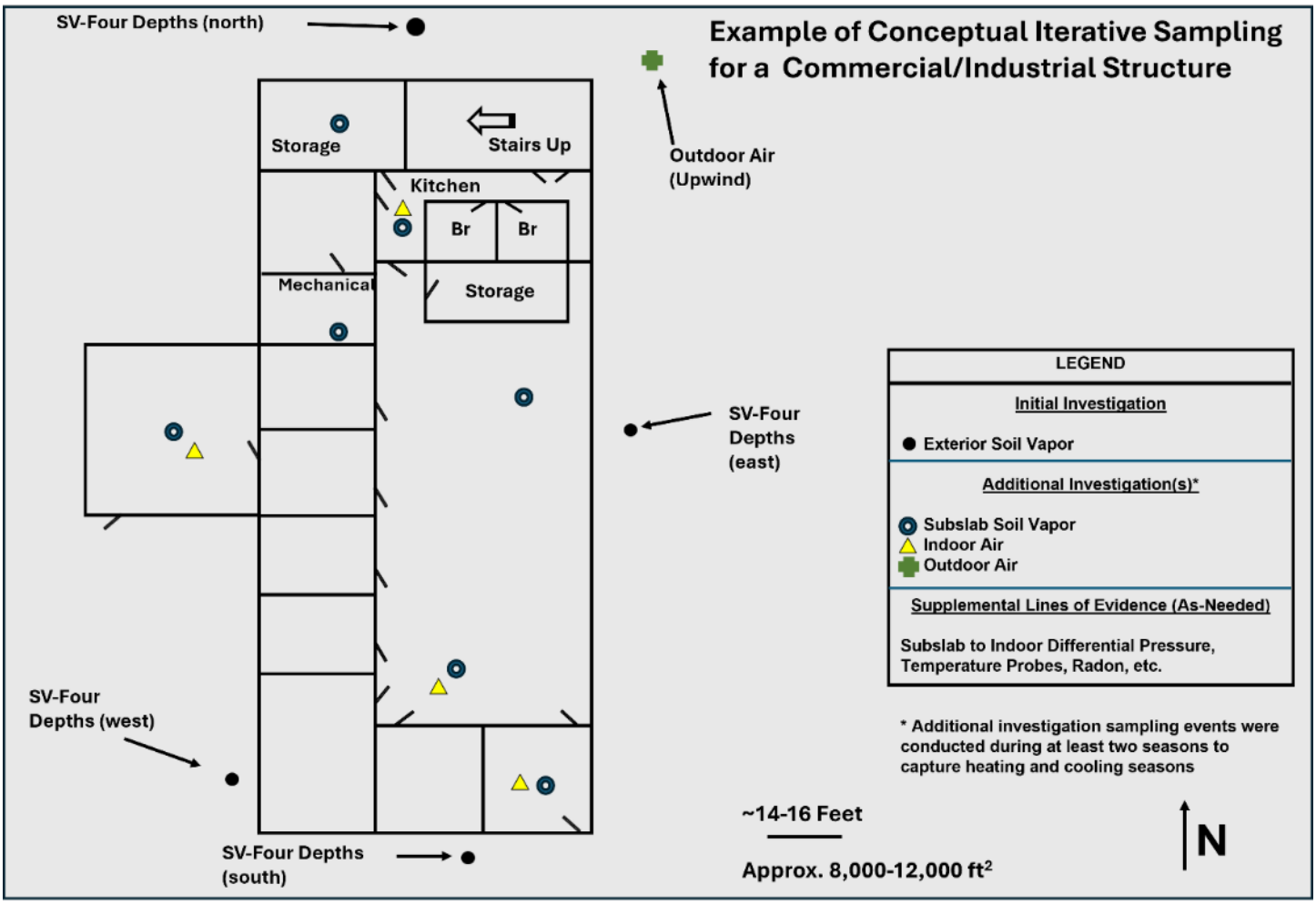


Figure 6-3. In this example, an initial investigation was conducted to determine whether vapor-forming chemicals are present in exterior soil vapor near a commercial/industrial building.

It is often beneficial to select several buildings for the initial investigation to account for uncertainty and ensure that the various factors influencing soil vapor migration are considered. For instance, the building overlying the highest concentrations of groundwater or soil vapor, as well as the building with the most susceptible foundation conditions, might both be investigated—regardless of whether one building clearly shows the highest concentrations.

Once a building is selected for investigation, the environmental media to be sampled and the frequency of sampling required to address the data gap will need to be included in the work plan. The practitioner should consider adequate spatial representation of the building and additional field parameters such as differential pressure and temperature, in the design of sample locations at a building. Figure 6-3 is a conceptual example of a hypothetical commercial/industrial building potentially impacted by groundwater migration from an off-site source that generally achieves adequate spatial and temporal VI characterization based on iterative CSM refinement (Chapter 4: Conceptual Site Model) and site screening results (Chapter 5: Site Screening). Figure 6-4 is an example of a building with insufficient spatial and temporal sample representation.

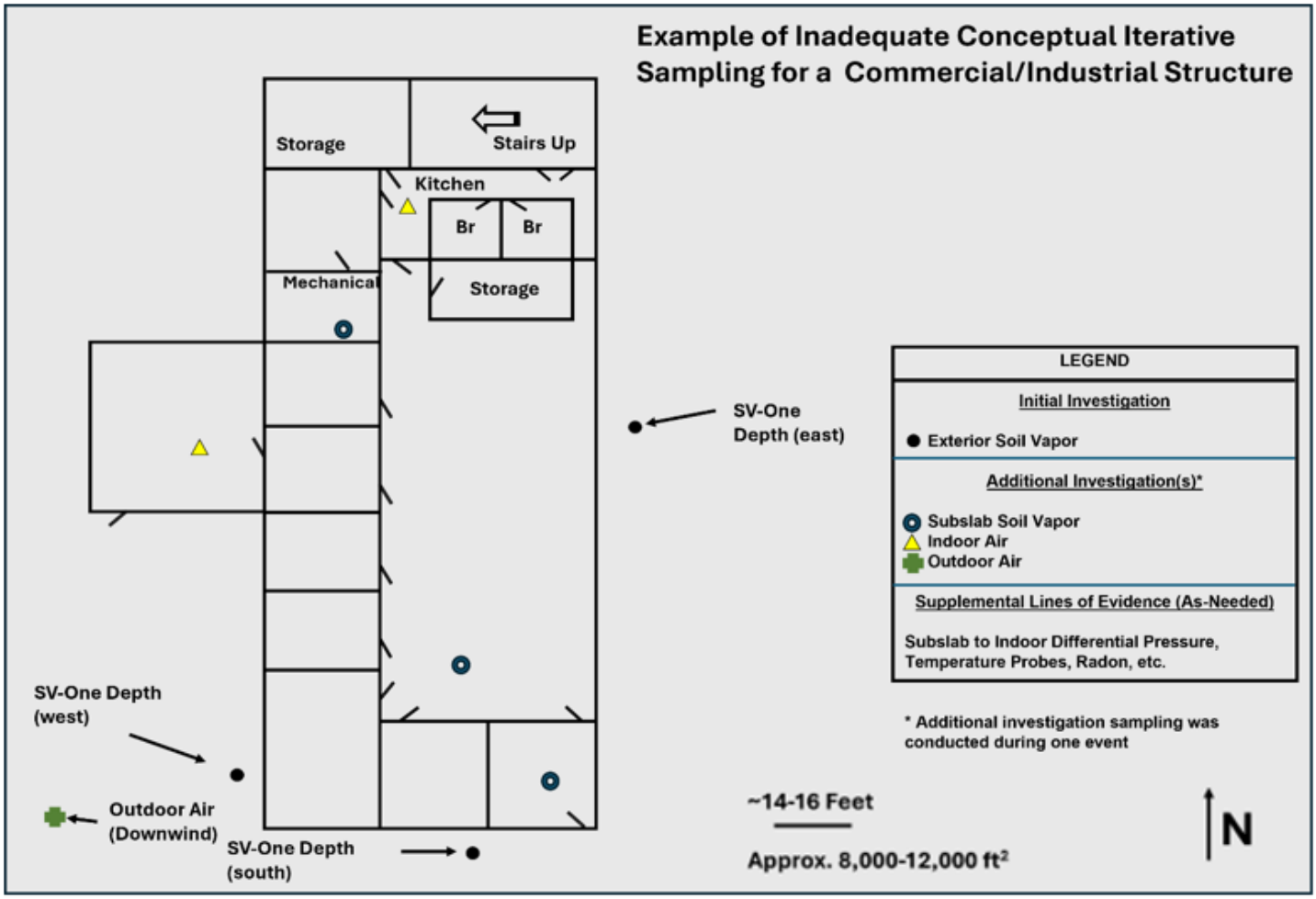


Figure 6-4. Example of inadequate conceptual iterative sampling for a commercial/industrial building.

Characterization of VI site conditions requires adequate soil vapor sample density to capture lateral and vertical spatial variability and data collection at an appropriate frequency to ensure temporal variability due to changes in weather conditions (temperature, wind, barometric pressure trend, etc.) and precipitation (soil moisture content) are captured. For a hypothetical commercial/industrial building of

approximately 8,000–12,000 square feet as conceptualized in Figure 6-4, the spatial sample collection is inadequate in the following respects:

- Two indoor air samples are insufficient for the building size and may not represent the areas nearest the potential sources or those occupied for long durations (Section 7.5.2).
- The outdoor air sample was collected from a downwind location (Section 7.5.3).
- Three soil vapor samples in a building this size does not provide sufficient sample density (Sections 7.5.4.2 and 7.5.4.7).
- Only one vertical exterior soil vapor sample depth was collected even though the primary VI concern is from off-site plume migration (see Sections 7.5.4.4 and 7.5.4.5).
- Soil vapor samples are not collected in all appropriate areas, such as chemical storage areas and near potential preferential pathways (Sections 7.5.4.3 and 7.8.2.1).
- The single sampling event fails to capture potential temporal variability (see Section 7.8.2.2).

Due to the site-specific nature of VI investigation, practitioners should always verify state and federal guidance, project DQOs, and site conditions when developing the sample plan. For additional information about media-specific sampling locations, delineation, and frequencies, refer to Section 7.5.

6.2.4. Background Sources

Multiple sources of chemicals may be affecting air quality, not all of which are a result of a VI pathway. These potential sources of VFCs, often referred to as background sources, should be noted during a building survey that is conducted as an initial step when completing an indoor/outdoor air investigation. For more information on conducting a building survey and identifying potential background sources, refer to Sections 7.3.1.1 and 7.8.2.3 in Chapter 7: Sampling and Analysis. Noting potential background sources may help to focus the analyte list to compounds identified in the subsurface at concentrations above applicable regulatory screening levels, their breakdown products, and/or any marker compounds that may be useful for assessing VI. Since state agencies have different requirements, the best practice is to confirm the analyte list with the appropriate regulatory agency. Defining which chemicals have been released into the subsurface and which are VFCs relevant to the VI pathway will be useful when interpreting indoor air data and potential background concentrations. In some circumstances, practitioners may determine indoor air background concentrations as part of an MLE approach in assessing VI (refer to the Background Sources to Indoor Air Fact Sheet for further details).

6.2.5. Sampling and Analysis Plan

Once data gaps are identified and investigative locations and frequencies are determined, sampling methodologies (see Chapter 7: Sampling and Analysis) and DQOs (see the Data Quality and Adequacy Fact Sheet) should be developed in conjunction with a sampling and analysis plan. This is an iterative process, and the investigative approach may need to be revised based on new data. For example, preliminary soil vapor samples might help identify which buildings should be sampled in greater detail. The analyte list and associated laboratory methods included in a sampling and analysis plan should at a minimum focus on chemicals that have either been identified as being potential COCs for the site or detected during previous investigations. The latter is particularly important for indoor air, as the focus on the sampling and analysis plan should be those analytes that had been previously detected in subsurface samples at concentrations above screening levels, as well as their possible breakdown products (see Table 8-1). Since a suite of analytes is site-specific and regulatory agencies have different requirements, confirm the analyte list in consultation with the project team including the appropriate regulators.

The CSM should be updated in parallel with the sampling and analysis plan. Sampling plans should be reviewed to ensure that the objectives align with the DQOs for the VI pathway. Detection limits for the chosen methods should be reviewed to ensure adequate sensitivity for detecting volatile chemicals at levels of concern. Media samples should follow relevant standard operating procedures (SOPs) and/or state guidance.

NOTE: It may be discovered that buildings with a specific design feature may be more susceptible to VI and warrant closer attention or proactive mitigation (e.g., buildings with dirt floor basements, wet basements, high levels of weatherization and low air exchange rates; very old houses; and buildings with abandoned plumbing fixtures (including floor drains). The building does not necessarily need to be located over the most highly contaminated area.

6.2.6. Community Outreach and Information Plan

Throughout the investigation, it is important to recognize that VI can significantly impact communities. Given the potential impacts of VI, it is essential to engage and communicate with communities in a transparent, compassionate manner. Communities often seek clear and definitive answers. For more detailed guidance on community outreach, refer to **Chapter 3: Community Engagement**.

6.2.7. Scheduling Investigation

Developing a schedule for VI investigations is critical, especially when access to off-site properties is required. The schedule must be flexible to accommodate potential changes and unforeseen challenges.

Key activities that should be reflected in the schedule include the following:

- Acquiring regulatory approvals
- Acquiring permits and local approvals
- Providing community education and acquiring access agreements
- Scheduling tests and addressing logistical challenges
- Evaluating data to determine adequacy
- Reporting and communicating results
- Preparing for risk management decisions

6.3. Step 3–Implement Work Plan

6.3.1. Complete Pre-Field Activities

Prior to executing the proposed sampling activities that are presented in a work plan, several tasks must be completed, including identifying and hiring the appropriate subcontractors (i.e., drillers, laboratories, geophysical surveyors, etc.). Ensuring that these tasks are properly completed prior to mobilizing to the field is key to a successful field investigation. Some of these tasks (e.g., the geophysical survey or obtaining permits) will be completed following the approval of a work plan, but it can be helpful to begin some tasks earlier. The following is a list of the most common pre-field tasks:

- **Site Visit:** While not always possible, it is generally good practice to conduct a site walk prior to developing a sampling plan. This allows a practitioner to take note of features that may obstruct various sampling locations.

- **Hiring subcontractors:** Practitioners should ensure that they hire the right subcontractors for each field task. For example, a project under regulatory oversight will typically require a driller with the proper state or local licensing. Ensuring that subcontractors are properly fitted for a task will help the project run smoothly.
- **Health and Safety Plan (HASP):** Prior to mobilizing to the field, practitioners should complete a HASP that includes any safety concerns that may come up during fieldwork (e.g., identifying hazards, acquiring training certificates, developing a map to the closest hospital, etc.). During field activities, practitioners should summarize important parts of the HASP to all on-site workers.
- **Quality Assurance Project Plan (QAPP):** A QAPP is a written document that outlines and describes the anticipated tasks for an entire project. This ensures that the investigatory portion of a project produces reliable data that can be used to meet the overall DQOs. A QAPP will provide details on applicable field procedures (e.g., soil vapor probe installation process and sampling procedures), field and laboratory methods, and quality assurance/quality control (QA/QC) samples that will be required. For many projects, a QAPP may be a stand-alone document; however, some smaller projects may incorporate the QAPP into an investigation work plan. Many state and federal oversight agencies require the development of a QAPP prior to mobilization for any investigation. Practitioners should make sure to check with their appropriate regulatory agency on these requirements. When required, practitioners should be sure to submit the project QAPP to the overseeing regulatory agency for approval prior to field mobilization.
- **Obtaining Permits:** Practitioners should ensure that all necessary permits are obtained prior to beginning fieldwork. Permits are generally required by various local agencies. For example, when drilling at a site to install soil vapor probes or groundwater monitoring wells, a drilling permit may be required by a city, county, or state. When those drilling locations are in a public right of way, an encroachment permit may be required by a local public works department. It should be noted that many local permits require that practitioners notify the permitting agency prior to beginning work. Field staff and project managers should make sure that they are familiar with and follow all of the permitting rules to avoid unnecessary work stoppages.
- **Access Agreements:** When performing an investigation that includes sampling locations on adjacent and/or nearby properties, practitioners will need to obtain permission from the property owner or their representative. In most cases, this means obtaining a signature on a legal access agreement that grants practitioners permission to perform investigatory tasks on the off-site properties. A verbal agreement may be sufficient depending on the local regulatory authority. The access agreements should clearly lay out all activities that will be performed. Since such permission is essential to the investigation, the community engagement plan should lay out a strategy for obtaining legal access to maximize the number of signed agreements. Refer to **Section 3.2.5 Property and Building Access** for additional information on developing a community engagement plan and see **Appendix B: Example Documents** for examples of access agreements. Practitioners should make sure they have copies of the access agreements when in the field.
- **Vendor Coordination:** Prior to starting (and during) a field investigation, practitioners should ensure good coordination with all necessary vendors. For example, all laboratories that will be used should be contacted to ensure that field staff are sent the proper sampling devices/containers and that all shipping requirements can be met (e.g., temperature control or hold times). Practitioners should also ensure that all proper materials are obtained (e.g., tubing, valves, field meters, tracer gases).
- **Utility Clearance:** Prior to performing any drilling activity, practitioners should take any necessary steps to ensure that soil borings are clear of underground utilities. These steps may include, but are not limited to, calling a local underground utility notifier (e.g., DigAlert in California), obtaining utility maps, performing a geophysical survey, and/or hand clearing a soil boring using a hand auger.

6.3.2. Complete Field Activities

Field activities should be documented and followed in accordance with the schedule in the sampling and analysis plan. If unexpected field challenges or schedule changes do arise, best practice is to engage with the regulatory agency to determine next steps to prevent delays in the investigation.

6.4. Step 4–Site-Specific Evaluation

If the site-specific evaluation (see **Chapter 8: Data Evaluation and Vapor Intrusion Risk Assessment**) indicates potential VI risks exist for a building, the building should move to either of the following next stages:

- Additional investigation
- Remedial action (see **Chapter 10: Vapor Intrusion Mitigation**)
- Mitigation (see **Chapter 10: Vapor Intrusion Mitigation**)

If the site-specific evaluation (see **Chapter 8: Data Evaluation and Vapor Intrusion Risk Assessment**) does not indicate potential VI risks exist for a building (i.e., it has been screened out), no further VI evaluation is necessary (see **Chapter 11:Vapor Intrusion Component Determination, Exit Points, and Closure**).

This portion of the page left blank intentionally. Next chapter begins on the following page.

CHAPTER 7: SAMPLING AND ANALYSIS

7.1. Introduction and Overview

The collection and analysis of media samples are critical to assessing a property for VI, as well as evaluating the performance (effectiveness) of VI mitigation and/or remediation. This chapter presents various sampling and analysis methodologies available for VI investigations and mitigation performance monitoring. This information will help you select the sampling techniques and analytical methods that will best meet the data objectives for targeted media (i.e., soil vapor, sub-slab vapor, and air). The most common sampling locations and sampling media for a VI investigation are shown in **Figure 7-1.** Each of these will be discussed in this chapter.

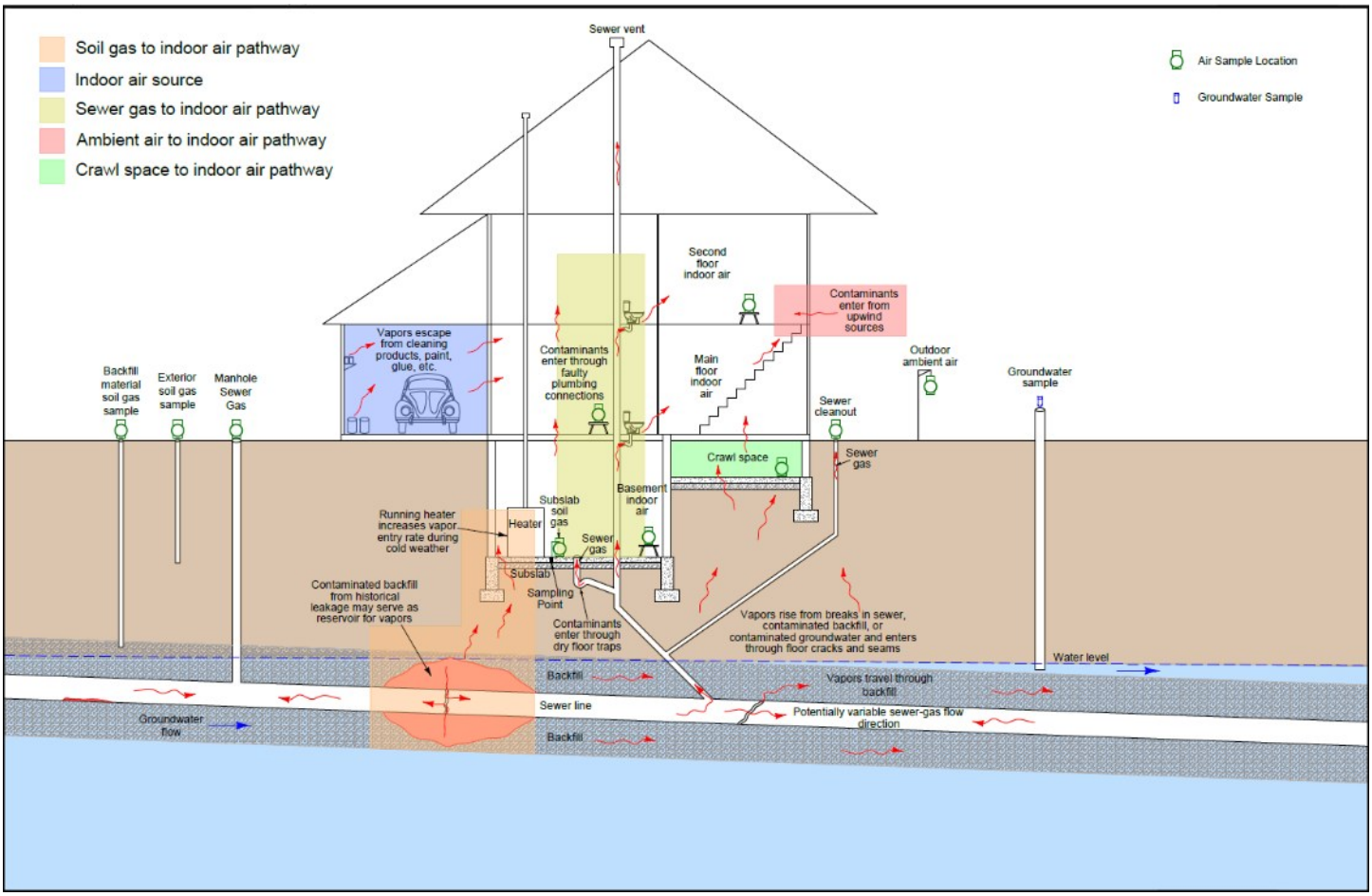


Figure 7-1. Example conceptual site model components and sampling locations displayed graphically.

Source: Laurie Chilcote, Association of Vapor Intrusion Professionals, used with permission.

For more information on the definitions of each type of media, where to find them, and their influence on the CSM, refer to **Section 4.2**. In many cases, the methods and tools described in this chapter are applicable to the investigation of both petroleum and nonpetroleum VFCs. Specifically, this section will help with the following tasks:

- Screening, identifying, and selecting sample locations

- Selecting the sampling technique considering media, sampling frequency, and sampling duration
- Selecting sampling techniques or approaches to reduce uncertainty related to factors including spatial and temporal variability, background sources, and preferential pathways
- Understanding the importance of sample collection processes to ensure data of appropriate quality
- Developing a list of appropriate questions for your lab
- Selecting the best analytical method for the required analysis
- Deciding on applicable field instruments

Defining an investigation's objectives and goals should always be part of project planning. Planning tools, such as the USEPA's DQO process, can help ensure that data of the appropriate quality, type, and amount are collected (USEPA 2006c). Clearly defining project objectives and goals also helps in selecting the appropriate sampling methods and locations. Data quality is defined within the discussion for each specific tool because quality limitations may differ according to the tool chosen.

Project goals and objectives are typically addressed during the preparation of an investigation work plan. While any planning process that follows the scientific method may be used, the USEPA's seven-step DQO process (USEPA 2006c) specifically addresses many of the issues that commonly arise during environmental investigations. Each step in a VI project will have different DQOs, but the process for establishing them should be consistent. A QAPP, which should be developed during the work plan phase of a project, prior to field mobilization, can assist practitioners in maintaining said consistency. Additional details on a QAPP are provided in **Section 6.3.1** and the **Quality Assurance Considerations Fact Sheet**. Further discussion of the DQO process, the importance of coordination between the sample collection team and the analytical laboratory, and other quality concerns can be found in **Section 7.10**. Additional investigation planning steps to consider prior to finalizing a sampling and analysis plan are presented in **Chapter 4: Conceptual Site Model** and **Chapter 6: Iterative Investigation Process**. It should be noted that practitioners should engage with the surrounding community throughout the entire life cycle of an investigation (i.e., from workplan development to sampling fieldwork and through reporting). For more information, refer to **Chapter 3: Community Engagement**.

Topics presented in this chapter include field-screening and real-time monitoring, collecting soil vapor/sub-slab vapor and/or indoor/outdoor air samples using both active and passive methods, strategies for determining sampling locations and frequencies, VI considerations when sampling other media (e.g., soil, groundwater, NAPL), analytical methods for VFCs, supplemental tools for collecting additional physical data that may affect VI, and considerations for sampling for PFAS. **Table 7-1** presents a summary of various sampling devices and the media they are applicable to.

Table 7-1. Sampling methods by media type / analyte / parameter.

Sampling Method	Soil Vapor	Sub-Slab Vapor	Indoor Air	Outdoor Air	Crawl Space	Sewer	VIPP[1]	Pressure/ Vacuum[2]	Mass Flux	Soil	Ground-water	NAPL
Handheld Logging Instruments[3]	●	●	●	●	●	●	◖	●		◖	◖	
Portable GC/MS	●	●	●	●	●	●	●					
Mobile Laboratory	●	●								●	●	
Evacuated Canisters	●	●	●	●	●	●	◖					
Pump-Collected Sorbent Tubes	●	●	●	●	●	●	●					
Air Sampling Bags	●	●										
Gas-Tight Glass Containers	●	●	●	●	●	●	●					
Glass Syringes or Bulbs	●	●				◖	◖					
Passive Sorbent Samplers[4]	●	●	●	●	●	●					◖	
High-Volume Sampling	●	●	●	●	●	●						
Active Groundwater Sampling Equipment											●	◖
Passive Groundwater Sampling Devices[4]											●	◖
High-Resolution In Situ Screening Tools[5]	◖	◖							●	●	●	●
Flux Chambers			●	●	◖				●			
Field GC (with various detectors)	●	●	●	●	●	●	●		●	●	●	

Notes:
Full circle = fully applicable; half circle = partially applicable; GC/MS = gas chromatography/mass spectrometry, NAPL = nonaqueous-phase liquid, VIPP = vapor intrusion preferential pathway.
1. Preferential pathways as defined by Section 4.2.16. Note that this includes sampling to confirm indoor sources of vapor-forming chemicals (VFCs).
2. This parameter refers to back pressure within a probe, a building's pressure, and the influence of atmospheric/barometric pressure.
3. Handheld instruments, as presented in Section 7.2, include those that collect measurements of VFC, such as a photoionization detector, and physical properties, such as a direct pressure sensor, differential pressure sensor, and a portable weather station (for barometric pressure trend, temperature trend, and wind speed and direction).
4. Refer to the Interstate Technology & Regulatory Council's Passive Sampling Technology Guidance document (ITRC 2024).
5. Examples of these tools include membrane interface probes and laser induced fluorescence.

7.2. Real-Time Data Collection

Reaching conclusions with a reasonable degree of confidence is challenging when there are only a handful of data points. VI data sets consisting of a limited number of soil vapor and/or indoor air analyses per property/building can be difficult to interpret. Cost and access limitations can preclude a larger number of sampling locations and/or multiple rounds of data collection. For sites with these challenges, real-time data collection tools may be a good option for assessing for VI.

A wide variety of devices can be used to assess the concentration of VFCs in a sample. The most rapid information is provided by highly portable handheld gas detectors. Handheld gas detectors are detectors with the sample drawn into an open tube with a small low-flow pump. Table 7-2 lists the most commonly used handheld gas detectors. The table also includes field-portable analytical devices, which are further described in the Real-Time Monitoring Fact Sheet. Instrument limitations, including chemical specificity and sensitivity (i.e., ability to achieve required reporting limits) are summarized in Table 7-2 and in the following subsections.

Handheld gas detectors are limited in sensitivity and have little or no chemical specificity. To surmount those limitations, detectors are hyphenated, or combined, with other technologies. For example, a GC separates the compounds in a sample so there are GC-FIDs, GC-PIDs, GC-electron-capture dissociation (GC-ECDs), GC- dry electrolytic conductivity detector (GC-DELCDs), and GC-mass spectrometry (GC-MSs). These devices provide better sensitivity and much more specificity, but they are not quite real time, as they require a few minutes for each analytical run. They provide rapid high-frequency data and are often deployed in the field (USEPA 2017c). Sensitivity is strongly influenced by the mode of sample collection, so another level of hyphenation is provided by the sampling method, with whole air, typically used with TO-15, or sorbent, typically used with TO-17. Some sorbent samplers can be deployed for times that make a mobile laboratory less advantageous, but this is not generally the case, especially when those sorbents are being used for PFAS.

The on-site analysis performed by real-time analytical tools (e.g., GC with appropriate detectors) can help identify preferential pathways (Section 4.2.16), indicate background indoor sources, allow for the field personnel to adjust sampling methods (e.g., switching from a whole-air method like USEPA TO-15 to an absorbent tube method like USEPA TO-17 when field screening indicates total VOCs are in excess of 1,000 ppm), and can be used to help design mitigation approaches and evaluate mitigation performance. Some systems are also used to monitor emissions and potential VFC intrusion concerns associated with aggressive remediation near occupied buildings (e.g., GC-ECD deployed in buildings where DNAPL thermal remediation is implemented).

Remotely operated analytical systems require attention to prevent data loss caused by power or internet disruptions. Prompt data reduction and frequent instrument calibration are often needed for longer monitoring campaigns. Some systems feature automated alerts that notify key personnel to respond quickly when data have not been received within a specified time. Automated calibration standard analysis can also be set up to continuously monitor system stability.

In addition, various types of mass spectrometers are deployed in mobile laboratories (e.g., GC-MS operated in selective ion monitoring (SIM), GC-MS-MS, proton transfer reaction MS, ion trap MS, cavity ring spectrometers, etc.; see Figure 7-2 and Figure 7-3 for examples). Each option will have levels of applicability related to their sensitivity, chemical selectivity, cost, and overall project objective. As such, it is important to understand what questions practitioners are trying to answer.

Table 7-2. Detectors used in handheld gas detectors and/or portable vapor analytical instruments.

Detector acronym	Detector name	Principal	Specificity	Sensitivity	Comments
FID	Flame ionization detector	The sample is subject to a flame, and the response is proportional to the intensity of the flame.	Very limited—responds to anything it can burn; often used to give a TPH concentration if used with a GC	Variable, but still limited	
PID	Photoionization detector	Exposes the sample to a light bulb, and the intensity of the response is proportional to the concentration of gases in the sample with an ionization potential equal to or less than the energy of the light provided by the bulb.	Depends on the choice of bulb used, but ideal for BTEX and chlorinated VFCs	Variable, but still limited	Not sufficiently sensitive for compliance measurements and VI pathways for many common analytes. Isobutylene is often used to calibrate a PID. When evaluating for a target chemical, a conversion factor may be needed. Refer to the manufacturer's instructions for applicable conversion factors.
DELCD	Dry electrolytic conductivity detector	Relies on unique properties of the chlorine and/or bromine released by high-temperature reaction of the input gas. The response is proportional to the concentration of chlorine and/or bromine in the sample.	Responds to all chlorinated and brominated chemicals	High for CVOCs and no response to most PHCs	Currently, the only field option for measuring indoor vinyl chloride to the detection levels required by most agencies.
MS	Mass spectrometer	Identify the sample chemicals by mass overcharge ratio.	High; often couples GC to achieve separation of chemicals and more accurate identification	High	Too heavy to be handheld, but available as a portable GC-MS. Analysis by GC-MS is routine work at certified environmental laboratories.
ECD	Electron capture detector	Uses a small beta emitter to generate electrons that are captured by analytes with a high electronegativity, and the response is proportional to the concentration of those charged analytes.	Only responds to molecules containing halogen atoms (e.g., chlorine)	Very sensitive to molecules containing 3 or more chlorine atoms such as PCE and TCE	GC-ECD is often used to study indoor air at PCE and TCE sites. It contains a 10 microcurie radioactive source that may require some additional certification. GC-ECD's dynamic range is narrower than GC-MS; therefore, stability may be an issue, and special attention should be paid to instrument calibration.

Notes: BTEX = benzene, toluene, ethylbenzene, and xylenes; CVOC = chlorinated volatile organic compound; GC = gas chromatography; m/z = ; PCE = tetrachloroethene; PHC = petroleum hydrocarbon; TCE = trichloroethylene or trichloroethene; TPH = total petroleum hydrocarbons; VFC = vapor-forming chemical; and VI = vapor intrusion.

7.2.1. Handheld Logging Instruments

Simple portable instruments can provide both qualitative and quantitative data depending upon the target chemical and the required detection levels. Handheld meters are composed of inlets plumbed directly to one or more detectors (see Table 7-2). In handheld devices there is no separation of the sample; all chemical specificity comes from the detector. Because these devices are essentially just a detector, they are often referred to by the name of the detector. Handheld field meters, such as PIDs, multi-gas meters, FIDs, and colorimetric (Draeger) tubes are useful tools for collecting initial screening data prior to or during the sampling process. For example, PID readings collected from soil, known as *headspace readings*, can help direct field personnel in determining the best depth intervals to install vapor probes during the drilling process (Figure 7-2). PID and multi-gas detector readings from soil vapor probes can be a first LOE in assessing total VFC concentrations when high parts per million by volume (ppmv) concentrations are expected or if additional safety precautions are needed when shipping a soil vapor sample (e.g., high levels of methane collected in SUMMA® canisters). PIDs are also often used to collect field readings from remedial systems, vent risers, and monitoring points to assess performance of a given remedial or mitigation measure. At sites with extremely high concentrations in the shallow subsurface and/or indoor air, colorimetric tubes can provide an initial screening concentration for a specific VFC, which can help in situations where increased personal protection equipment may be warranted (e.g., respirators).



Figure 7-2. Photographs showing how to screen soil for headspace measurements using a photoionization detector. These measurements can be collected from a glass jar covered in aluminum foil (left) or a baggie (right).

Source: Environmental Science and Technology, used with permission.

Most handheld field-screening instruments are limited to the ppmv range, which may not provide sufficient resolution and result in false negative results. Quantitative oxygen and carbon dioxide data can be obtained from handheld portable meters for concentrations in the percentage range. Handheld portable methane instruments are available that measure in both the percentage and ppm ranges. Helium detectors are available with a range of 0.01%–100% by volume.

When using these meters to collect screening data in the field, personnel should take a few steps and precautions:

- A multi-gas meter with a PID may be better suited for soil vapor sampling while a PID meter alone may be better for soil sampling. This includes different versions of the same meter. When sampling soil vapor, a PID set to read in ppm may suffice, but for indoor air, parts per billion is better. PIDs use a high-energy ultraviolet (UV) light source to ionize chemicals and come with a variety of lamps that vary in ionization potential (measured in electron volts [eV]). The most common (default) is the

10.6 eV lamp, but 9.8 eV (limited chemicals detected) and 11.7 eV (broad range of chemicals detected) are also available. PIDs will only detect chemicals that can be ionized by the UV lamp in the respective unit, so selecting the appropriate lamp eV is critical for detection of the site VFCs.

- At a minimum, always calibrate the meter at the beginning of a field day. Most manufacturers also recommend checking the calibration of the meter throughout the day, particularly after a series of elevated readings, and at the end of the day.
- Always know the action levels for a given contaminant. These should be established and easily found in the HASP for a site.
- When collecting headspace readings from soil, be sure to allow the soil to sit in the sample container for at least 10 minutes to allow for VFCs to come to equilibrium within the headspace of the sample container.
- Never attach the handheld meter directly to the tubing of a soil vapor probe. Soil vapor should first be collected in a separate container (e.g., an air sampling bag or syringe), and then the reading collected from the container.

Photographs of some of these handheld logging tools are shown in **Figure 7-3** below.



Figure 7-3. Examples of handheld screening devices for use in the field, including two photoionization detectors (top left and bottom left), two multi-gas meters (top center), a flame ionization detector (bottom left-center), colorimetric gas detection tubes with pump (bottom right), and an MGD-2002 helium detector (top right).

Source: Pine Environmental Services LLC, used with permission.

7.2.2. Real-Time Chemical-Specific Analyzer

Real-time chemical analyzers vary in design, output, accuracy, and application; thus, not all analyzers are appropriate for all types of investigations. As presented in Section 7.2.1, although several real-time analytical devices have been commercially available for decades, most are not analyte-specific and have been more suitable for general screening purposes. In recent years, newer real-time chemical-specific analyzers have been introduced that meet very specific detection objectives, some of which can detect and quantify specific compounds in a mixed chemical gas stream.

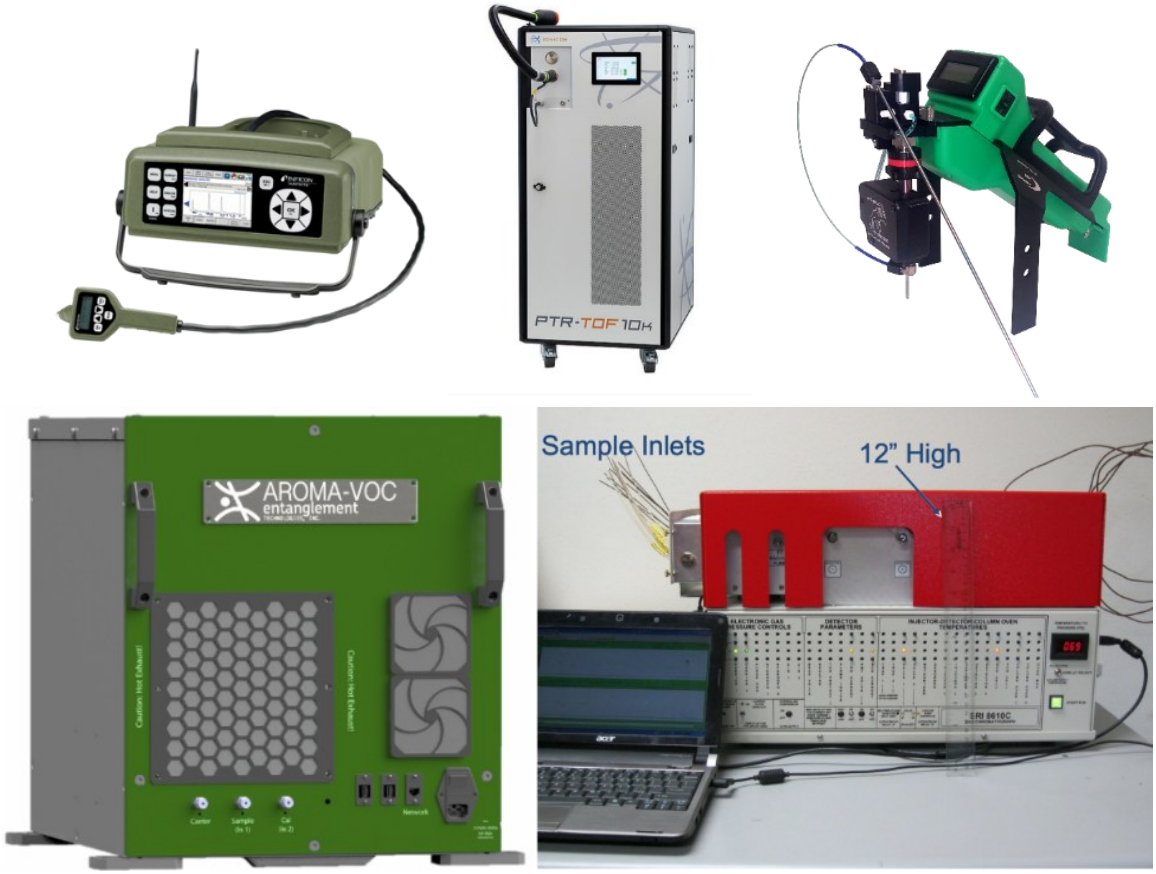


Figure 7-4. Inficon Hapsite (top left), Defiant Technology's portable GC/frog (top center), proton transfer reaction mass spectroscopy system (top right), cavity ring-down spectroscopy system (bottom left), and automated continuous field gas chromatograph with stream selector valve and internet connection (bottom right).

Sources in same order: Inficon, Defiant Technology, Entanglement Technologies, Ionicon, VaporSafe, used with permission.

A GC column is typically composed of tubing with an internal coating to separate mixtures of chemicals into individual chemicals that can be identified by the time required for each compound of interest to pass through the column. This is referred to as the *residence time* or *retention time*. In general, compounds with heavier molecular weight pass through the column at a slower rate than lighter compounds. Some GC devices are equipped with a stream selector valve that allows for automated sampling and analysis from multiple locations with a single analytical instrument (Hosangadi et al. 2017; Kram et al. 2016; 2019; 2020; 2022). The sensitivity and selectivity will depend upon the detector, the pre-detection sample preparation (e.g., sorbent focusing trap), and whether groups of chemicals are separated prior to being introduced to the detector. Several of the commercially available real-time

chemical-specific analyzers are shown in Figure 7-4. For details on real-time monitoring methodology, refer to the Real-Time Monitoring Fact Sheet.

An advantage of using real-time chemical-specific analyzers is the ability to collect location-specific continuous monitoring data in a reduced number of mobilizations, which, for some projects, can greatly reduce costs. These data can be useful for identifying problem buildings, vapor entry and transport pathways, and indoor sources of VFCs; evaluating mitigation performance; and making empirical estimates of building-specific AFs. Continuous analyzers can sort out background scatter and determine temporal variations both indoors and below ground. These can also be used to initially screen buildings for potential indoor VFC sources. Larger data sets allow trends in the results to be recognized and correlated to other variables such as pressure differentials, wind speed, and HVAC systems and allow forensic approaches to be applied.

For more details about real-time chemical-specific analyzers and their uses in real-time data collection, see the Real-Time Monitoring Fact Sheet.

Note that additional real-time on-site methods that are currently less commonly used in VI investigations, but that can be used to meet specific investigative objectives, include mobile spectrometer systems (e.g., proton transfer reaction mass spectrometry, ion trap mobility spectrometry, cavity ring-down spectroscopy, and USEPA's trace atmospheric gas analyzer platform). In addition, continuous monitoring systems can be used during building pressure cycling, high-purge volume sampling, and for monitoring radon (radon-222), thoron (radon-220), hydrogen, and other types of tracer tests. Some of these approaches can be operated in continuous monitoring mode, while others require manual sampling prior to on-site analysis.

7.2.3. Mobile Laboratories

For sites that require lower detection limits, particularly for soil vapor and sub-slab vapor, practitioners may choose to use mobile laboratories, which are capable of producing real-time data while meeting method-required QA/QC, such as data validation. These mobile units, as shown in Figure 7-5, are equipped with laboratory-grade instruments, including GCs and MSs, and are capable of detection limits as low as 1–100 ug/m^3. Mobile laboratory samples are typically collected from temporary and/or permanent soil vapor and/or sub-slab vapor probes. For details on probe installation methods, refer to Section 7.3.4 and/or the Soil Vapor Probe Installation Toolbox Fact Sheet. For additional information on sampling and analytical methods used by mobile laboratories, refer to Section 7.2.3 and 7.10, respectively.



Figure 7-5. Exterior (left) and interior (center) of a typical mobile laboratory, and a sample being injected into the mobile laboratory's gas chromatograph / mass spectrometer (right).

Source: H&P Mobile Geochemistry, used with permission.

7.3. Methodologies for Installing Media Sampling Points

To collect media samples, a sampling device, point, or container must be deployed or installed that will allow for the collection of said media. Media samples can be collected using either active or passive sampling technologies. Active sampling uses a pump or the vacuum of a stainless-steel evacuated canister to collect the specific medium either inside a sampling vessel or onto an adsorbent. Passive sampling is based on the diffusion of a compound onto an adsorbent, without use of a vacuum or pump. Installation/deployment of sampling points may differ depending on the use of active versus passive collection methods. The following subsections present the primary methodologies for deploying/installing indoor/outdoor air samples, crawl-space samples, sub-slab vapor probes, and soil vapor probes for active and passive sample collection. When installing a sampling probe in the subsurface, it should be properly capped or abandoned after use to prevent the creation of a continuous conduit for soil vapor migration to indoor or outdoor air. For details on where to find each media within a site, refer to **Figure 4-1** in **Chapter 4: Conceptual Site Model**.

7.3.1. Indoor and Outdoor Air Sampling Points

7.3.1.1. Building Survey

When sampling for indoor and/or outdoor air, the chosen sampling device must be placed in the desired sampling location so that a representative sample is collected. When collecting both indoor and outdoor air samples, it is good practice to perform a building survey that documents any chemicals that are used/stored within the building (e.g., cleaning products, solvents, and/or petroleum products), observed preferential pathways and vapor entry points (see **Chapter 4: Conceptual Site Model**, **Section 4.2.16**), and any other condition that may be an indoor source of VFCs (e.g., new carpeting). An example building survey form is included in **Appendix B: Example Documents**. Practitioners should always check local regulatory guidance for any agency-specific building survey forms, as some states may require specific questions to be answered during a building survey. Examples from Vermont, California, and Minnesota are provided in Appendix B. Predetermined indoor and outdoor air sampling locations are typically presented in a work plan or sampling and analysis plan prior to mobilization to a site. Final sampling locations should be adjusted based on the findings of the building survey.

Typically, sampling is performed under normal HVAC operations. In other words, if an HVAC system is normally on during operations, it should remain on during sampling. Some states, such as California, recommend that a sampling event be conducted under both HVAC-on and HVAC-off conditions for comparison purposes (California DTSC 2023). The HVAC conditions should be recorded on the building survey forms.

It is important that all potential background sources for both indoor and outdoor air be noted during the building survey. For more information, refer to the **Background Sources to Indoor Air Fact Sheet**.

7.3.1.2. Placement of Sampling Devices

Air samples can be collected using either active or passive methods. When sampling, the collection device for an active (see **Section 7.4.1**) or passive sample (see **Section 7.4.2**) will be placed at a targeted location within the breathing zone (3–5 feet [0.9–1.5 m] above ground). For active sampling of indoor air, this can be accomplished by placing the sampler on a chair, table, portable stand, etc. For active outdoor air, the sampler can be secured to a pole, fence, portable stand, etc. When the active sampler must be placed on the floor/ground, tubing can be attached to a stick or pole that rises to the desired height. When passive sampling, the collection device is typically hung from the ceiling, a pole/fence, stand, etc. Outdoor air sampling devices should be placed outside of a building's and/or tree's dripline and protected from inclement weather (i.e., rain or snow). In some cases, the sampling devices may have to be secured

to avoid disturbance or tampering by the public. To avoid biased analytical results, practitioners, when able, should also ensure that air sampling vessels are not placed near indoor sources; however, if they cannot be avoided, the field personnel should note their proximity in the field log. It is also good practice to deploy air sampling vessels in the vicinity of preferential pathways, such as bathrooms and kitchens. For these locations, practitioners should attempt to remove any chemicals approximately 24 to 48 hours prior to deployment. Indoor air sampling locations should also target rooms and spaces with sensitive receptors and/or those that are most used by employees/residents/students/etc. For example, family rooms at a residential home, offices or breakrooms at a commercial/industrial building, or classrooms in a school. For more on determining proper locations of indoor and outdoor air samples, refer to **Sections 7.5.1** and **7.5.3**, respectively.

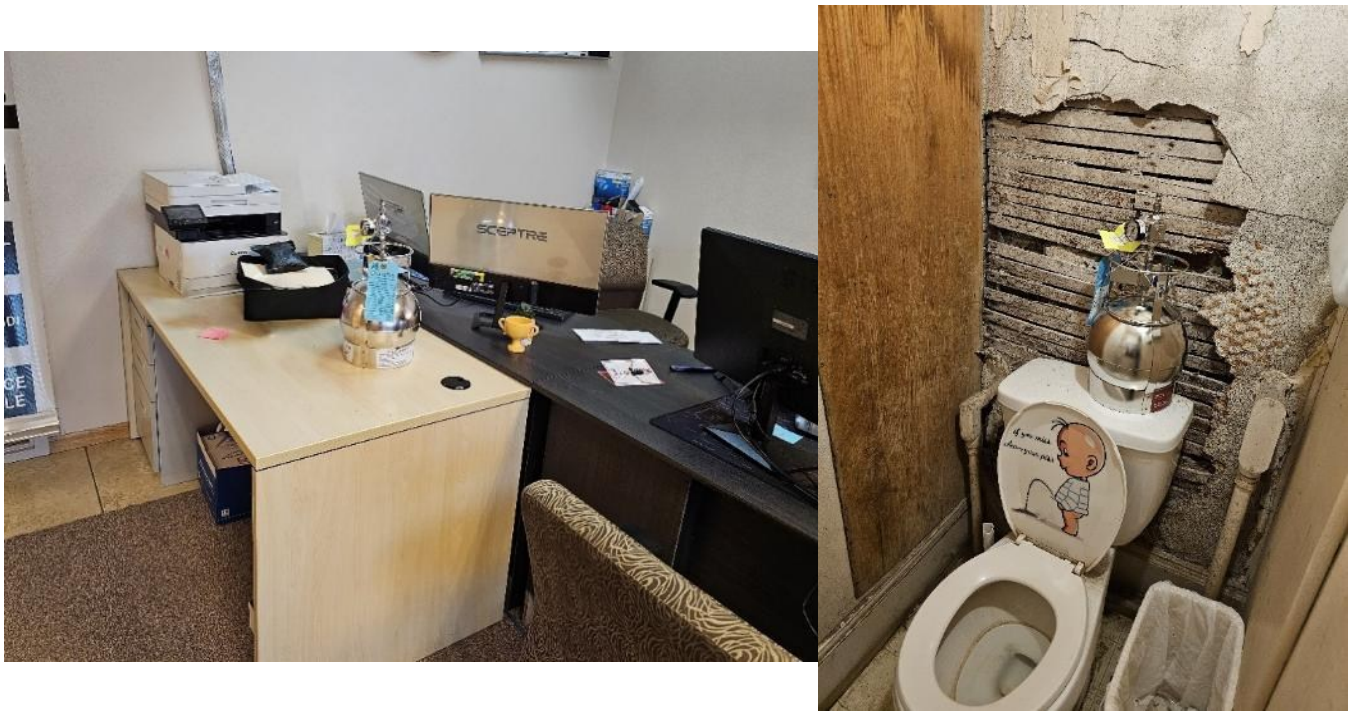


Figure 7-6. Active indoor air sample being collected using a passivated/evacuated canister. Note the placement in a bathroom (right) that contains multiple common preferential pathways.

Source: California Department of Toxic Substances Control, used with permission.

Figure 7-6 and **Figure 7-7** show examples of properly deployed active indoor and outdoor sampling devices. **Figure 7-8** shows examples of properly deployed passive indoor and outdoor sampling devices. Additional details about active sampling methods for indoor and outdoor air can be found in **Section 7.4.1**. Additional information about sampling locations and frequencies for indoor and outdoor air can be found in **Section 6.2.3**. For more information on the proper deployment and use of several passive indoor and/or outdoor air sampling devices, refer to ITRC's *Passive Sampling Technology Guidance* (ITRC 2024).



Figure 7-7. Active outdoor air sample being collected using a passivated/evacuated canister. Note that canisters may require being secured from theft using a chain (right).

Source: California Department of Toxic Substances Control, used with permission.



Figure 7-8. Passive air samplers deployed to collect indoor (left) and outdoor (right) air.

Source: Beacon Environmental, Inc, used with permission.

7.3.2. Crawl-Space Sampling Points

Like indoor and outdoor air, crawl-space samples can be collected using either active or passive methods. It is more common for practitioners to sample non-permit–required crawl spaces. For active crawl-space samples, the collection device should be placed on the ground or floor beneath the building, if possible. Note that a multi-gas meter should be used to verify that crawl-space conditions are appropriate for human occupancy prior to entry. When the crawl space is too small to enter, the sampling

device can be placed inside or outside of the building with tubing that runs to the desired location within the crawl space itself. If the size of the entry is large enough, this may be done by attaching the tubing to a rigid pole (made of an inert material) to allow tubing to be placed in the desired location within the crawl space. If placed inside the building, the tubing is typically inserted through a crack in the floor. Should it be necessary to drill a hole in the floor for the tubing, the practitioner should ensure that the annular space around the tubing is sealed.

Figure 7-9 shows an example of a properly deployed active crawl-space sampling device, while Figure 7-10 shows an example of a properly deployed passive crawl-space sample. Additional details about sampling methods for crawl-space samples can be found in Sections 7.4.1 and 7.4.2. Additional information about sampling locations and frequencies for crawl-space sampling can be found in Section 7.5.2. For more information on the proper deployment and use of several passive crawl-space sampling devices, refer to ITRC's *Passive Sampling Technology Guidance* (ITRC 2024).



Figure 7-9. Active crawl-space sample collection using passivated canisters.

Source: Vapor Pin Enterprises, Inc, used with permission.



Figure 7-10. Passive crawl-space sample collection.

Source: Vapor Pin Enterprises, Inc, used with permission.

7.3.3. Active Sub-Slab Vapor Probe Installation

A typical, active sub-slab vapor probe is installed by first drilling a small-diameter hole through the concrete slab, then inserting the vapor implant into said hole. The diameter of the hole is dependent upon the particular device or implant being constructed/used, and the hole should be drilled through the entire thickness of the slab. The bottom of the probes either float within the hole of the slab or extend to the base of the slab (see Figure 7-11 and Figure 7-12). A permanent sub-slab vapor probe can be field-constructed using ⅛- or ¼-inch outer diameter stainless-steel (or other inert material, such as Teflon®, high-density polyethylene [HDPE], polyether ether ketone [PEEK], or Nylaflow®) tubing, which is typically terminated at the surface with either a compression or barbed fitting. These field-constructed probes are grouted in place using hydraulic cement and are capped at the surface to prevent airflow from the surface (Figure 7-13). Temporary field-constructed sub-slab vapor probes can also be installed using the same size tubing; however, a temporary seal, such as hydrated granular bentonite or an inert modeling clay, is

used to prevent the airflow from the surface. Permanent construction is preferred for sites where additional data will be required over time. Advantages of field-constructed sub-slab vapor probes are their costs and that they can be easily customized (i.e., length of tubing, length of probe that sticks out of the ground, etc.) to adjust for site-specific conditions. Disadvantages of this installation method include difficulty of installation and that the attachment/detachment actions that happen during repetitive sampling events can eventually loosen the probe from the cement. If repeated sampling is anticipated, sub-slab probes' surface completion should be flush (trip-proof) and cosmetically clean, especially in residences.

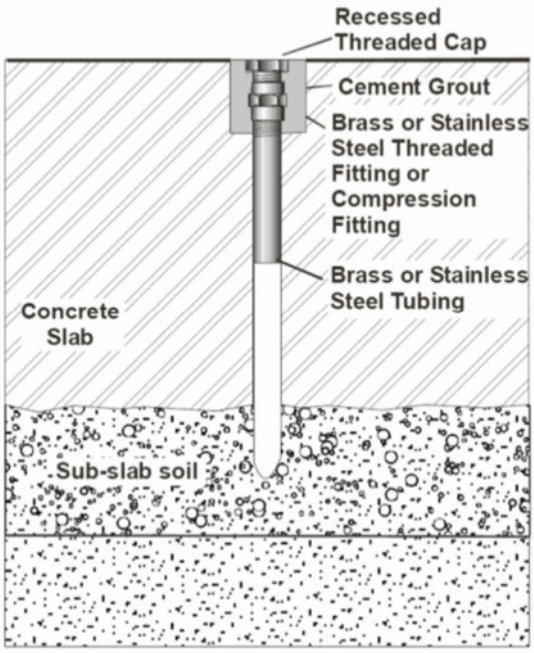


Figure 7-11. General schematic for installation of field-constructed sub-slab vapor probes.

Source: USEPA (2006b), used with permission.

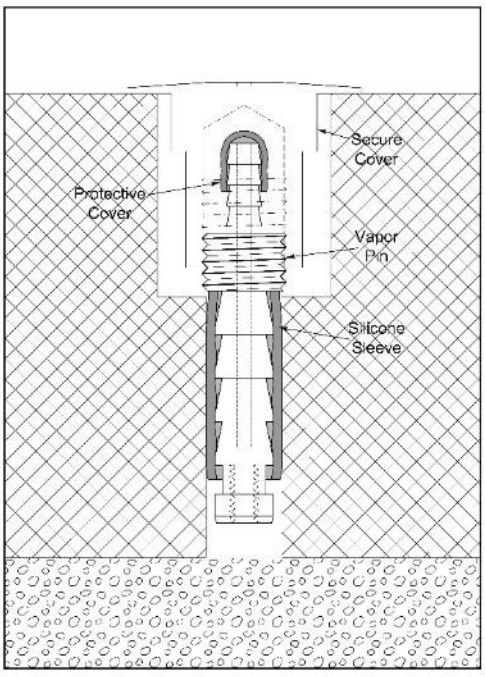


Figure 7-12. General schematic for an installed preconstructed sub-slab vapor probe.

Source: Vapor Pin Enterprises, Inc, used with permission.

Preconstructed sub-slab vapor probes can also be installed for both active and passive sampling. Commercially available preconstructed sub-slab probes consist of a stainless-steel or brass body within a silicone sleeve and typically have an overall outer diameter of ¾ inch. These devices are driven into the slab via a ⅝-inch diameter hole, providing an immediate compressive seal (**Figure 7-14**). The tops of these devices can be completed using a number of connection types, including barb, compression, and quick-connect fittings. Like the field-constructed probes, the preconstructed probes are typically completed flush with the surface. Advantages of these devices are ease of installation and that repeated connection actions do not jeopardize the seal. A disadvantage of these devices is their higher cost; however, the cost is typically offset by the reduced cost of labor required for installation and sampling. In addition, it should be noted that some of these devices can be easily extracted for reuse and can be reinstalled with passive samplers connected to their bases.



Figure 7-13. A photograph collage showing the installation process for a field-constructed sub-slab vapor probe (left) and a completed probe with compression fitting port (right).

Sources: Hawai'i State Department of Health's Hazard Evaluation and Emergency Response Office (left); A. Leavitt, PG, 2016 (right).

Both field-constructed and preconstructed sub-slab vapor probes can be installed as temporary or permanent. Limited research has shown that permanent and temporary probes provide comparable data (Zimmerman et al. 2017). For the field-constructed installation method, inert tubing (with or without an affixed implant) can be inserted into the drilled hole and sealed with nonvolatile-emitting and non-shrinking material, such as modeling clay or beeswax. When twisting the tubing into the hole during installation, Teflon tape can also be used to create a tight fit (NJDEP 2024). Some state guidance, such as New York's, includes a list of permissible materials that can be used for sealing temporary field-constructed sub-slab vapor probes (NYSDOH 2006). Like permanent probes, the tubing used for temporary field-constructed sub-slab vapor probes will typically be terminated at the surface with either a compression or barbed fitting. As noted above, most preconstructed sub-slab vapor probes can be easily removed, decontaminated, and reused. As such, these devices are well suited for use as temporary probes. When doing so, only the preconstructed metal probe itself should be reused. A new piece of silicone tubing should be used for the seal. A practitioner should always check with the manufacturer of a preconstructed probe to ensure repeated use is acceptable.

SOPs for sub-slab sampling were published by USEPA in March 2006 (USEPA 2006a), April 2021 (USEPA 2021), and April 2023 (USEPA 2023). The New Jersey Department of Environmental Protection (NJDEP) (2018; 2024), Ohio Environmental Protection Agency (2020), and the California Environmental Protection Agency's (CalEPA's) Department of Toxic Substances Control (DTSC) (2015) have modified versions of these procedures in their guidance documents.

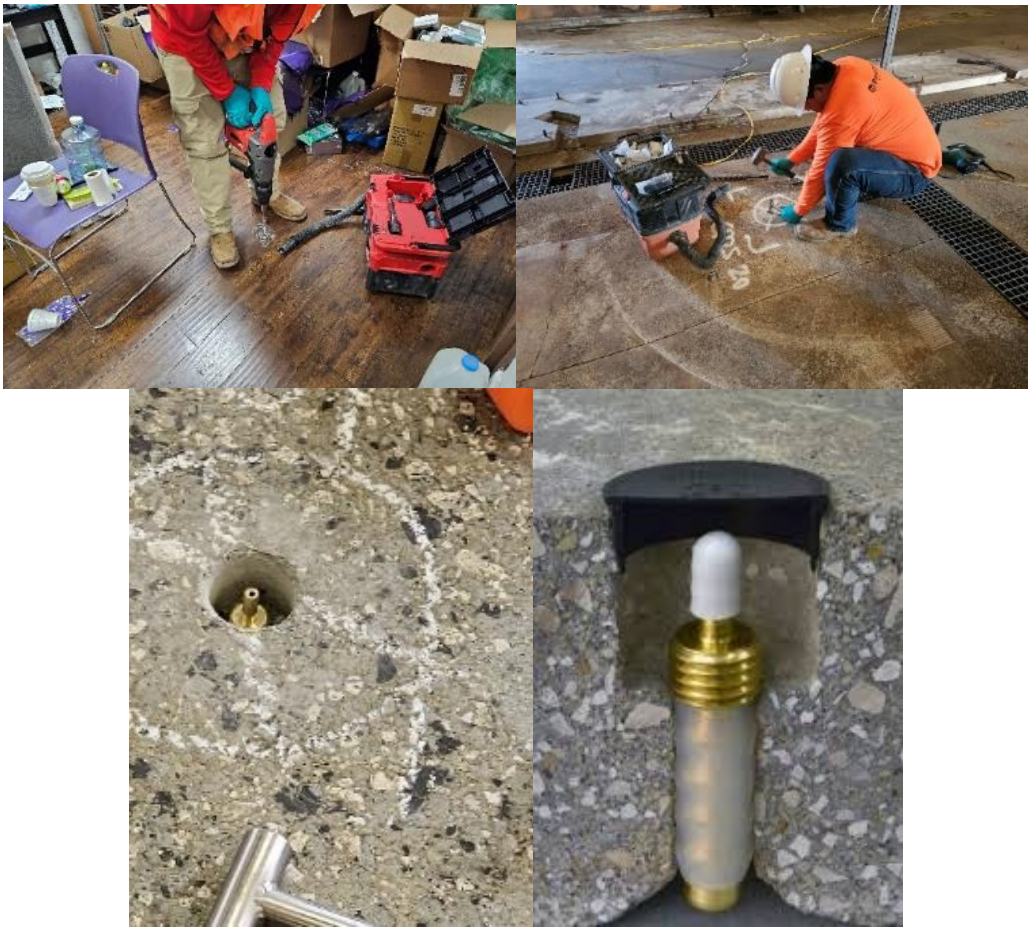


Figure 7-14. Photographs of the installation process of a preconstructed sub-slab vapor probe (top), a complete preconstructed sub-slab vapor probe (bottom left), and a cross-section photograph for a preconstructed sub-slab vapor probe (bottom right).

Sources: California Department of Toxic Substances Control (top left, top right, and bottom left); Vapor Pin Enterprises, Inc. (bottom right), used with permission.

It is recommended that practitioners complete a ground-penetrating radar survey prior to installing any sub-slab vapor probes to avoid rebar and subsurface utilities that may be embedded in the slab.

7.3.4. Active Soil Vapor Probe Installation

Soil vapor sampling is the preferred sampling and investigative tool for most VI investigations. To perform active soil vapor sampling, a soil vapor probe must first be installed at a desired location. The two techniques most commonly used to install soil vapor probes for active soil vapor sampling are driven probe rod and burial of soil vapor sampling tubes (driven probe and probe burial methods, respectively). Both methods have been shown to give reliable, reproducible data in moderate- to high-permeability soils (USEPA 2006b).

The driven probe method consists of the insertion of a hard rod (probe) driven to a target depth, collection of soil vapor through the rod while it is in the ground, and subsequent removal of the rod (Figure 7-15). This is most commonly used to install temporary soil vapor probes. The probe burial method consists of the installation of a small-diameter (typically ⅛- to 1-inch outside diameter [OD]) inert (e.g., stainless-steel, Teflon®, HDPE, PEEK, or Nylaflow®) tube or pipe at a target depth (Figure 7-16 and Figure 7-17). Soil

vapor is subsequently sampled after a period of time (also known as the equilibrium time). Before choosing an installation method, practitioners should confirm whether their applicable regulatory oversight agency has either a preferred method or local installation requirements that differ from this guidance. In some cases, soil vapor samples may be collected from existing groundwater and/or SVE wells. When this is done, new soil vapor probes are not installed. For more details regarding sampling from groundwater wells, see **Section 7.4.3**. For further details about these two installation methods, refer to the **Soil Vapor Probe Installation Toolbox Fact Sheet**.

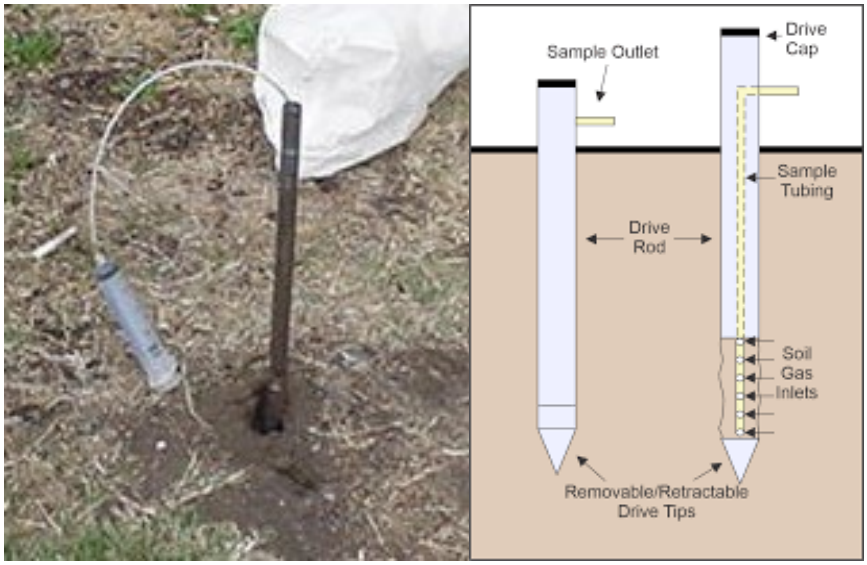


Figure 7-15. Photograph (left) and diagram (right) of a driven soil vapor probe.

Source: H&P Mobile Geochemistry (left); New Jersey Department of Environmental Protection (right), used with permission.



Figure 7-16. Diagram (left) and photograph (right) of a typical dual-nested soil vapor probe installed using the burial method.

Source: H&P Mobile Geochemistry (left); California Department of Toxic Substances Control (right), used with permission.



Figure 7-17. Photographs of multi-nested (left) and triple-nested (right) soil vapor probes. Note that the probes on the right are temporary but were installed using the burial method.

Source: H&P Mobile Geochemistry, used with permission.

7.3.4.1. Underground Utilities

For all soil vapor probe installation methods, underground utilities should be located prior to installation and avoided during ground-penetrating activities. Underground utilities are typically located by completing a geophysical survey or advancing a boring using hand-digging methods (e.g., hand auger or air knife) to 5 feet below ground surface (bgs). For sites with sensitive underground utilities, such as service stations, it is not recommended to use an air knife to clear sample locations. Furthermore, an air knife causes significant subsurface vapor movement and should only be used as a last resort when evaluating VI. If an air knife is used, additional equilibrium time will be required.

7.3.4.2. Soil Vapor Probe Materials and Construction

It is important that soil vapor probes are constructed properly using the correct materials:

- Tubing material with the correct diameter: most commonly ⅛-inch or ¼-inch outer diameter nylon, Teflon, or stainless-steel tubing.
- Vapor probe tip (or implant): typically, stainless steel, aluminum, ceramic, or plastic
- Sand pack: the right size for both the formation and probe implant (i.e., sand)
- Seal: often hydrated granular bentonite or grout
- Surface terminations and fitting for the tubing: stainless-steel or plastic ball/3-way valves, compression caps/plugs, or rubber tube covers
- Surface completion: a seal using bentonite or modeling clay for temporary probes versus accounting for the existing surface (i.e., grass or a traffic-rated well box) for permanent probes

Figure 7-18 through Figure 7-20 below show examples of some of materials mentioned above. For further details about these materials, refer to the Soil Vapor Probe Installation Toolbox Fact Sheet.



Figure 7-18. Photographs of typical soil vapor probe implants.

Source: Environmental Services Products (ESP Supply), used with permission.



Figure 7-19. Photographs of typical soil vapor probe tubing, including high-density polyethylene (left), Nylaflow (center), and Teflon (right).

Source: ESP Supply, used with permission.

7.3.4.3. Equilibration Times

When probes are installed, the in situ soil vapor/sub-slab vapor can be displaced. Therefore, a period of equilibration time is required for the soil vapor/sub-slab vapor to equilibrate to its predisturbed values. Several states stipulate preferred equilibration times in their regulatory guidance documents (California DTSC 2015). The equilibration time in some states depends on the investigation objectives and/or data quality requirements, and a less-than-ideal equilibration time may be acceptable if a soil vapor survey is conducted using temporary points to map the extent of a vapor plume and/or the sample data are not intended for use in risk assessment or site closure decisions. Many states base the equilibration times on the drilling method used to install because different methods disturb in situ soil to varying degrees. For example, California requires between 2 and 48 hours for probes installed using direct push drilling, 48 hours for probes using hand auger or hollow-stem auger drilling, and between three days and three weeks for probes installed using rotosonic drilling (California DTSC 2015). Some states have based their equilibration times on the installation method (i.e., driven probe versus probe burial methods mentioned above; Schumacher et al. 2016). As presented in Section 7.3.4.1, it may take several days for equilibrium in the soil to be reestablished when an air knife is used.



Figure 7-20. Photographs of common materials used during the soil vapor probe installation process, including granular bentonite (top left), sand (top center), plastic three-way valves (bottom left and bottom center), compression valves (top right), compression fittings (center right), and a well box (bottom right).

Source: ESP Supply, used with permission.

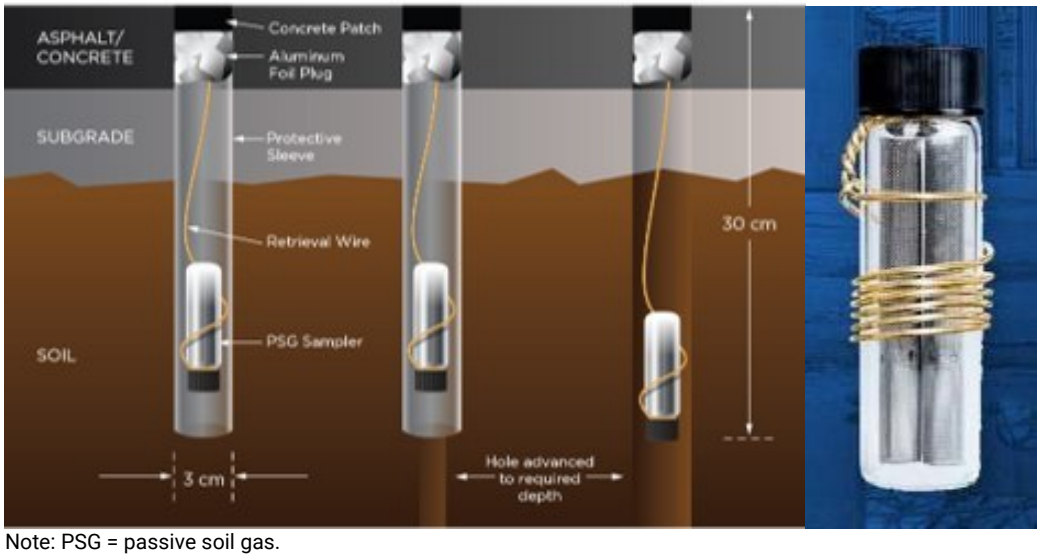
Given this range of strategies that are currently used throughout the country, the following recommended minimum equilibration times have been compiled:

- Permanent and/or semi-permanent probes that are buried in a sand pack and sealed with hydrated bentonite should be allowed to equilibrate for 24 to 48 hours following installation. Note that a minimum of 48 hours is strongly encouraged for more reliable data.
- If rotosonic drilling is used to install permanent and/or semi-permanent probes, extended equilibration time (more than two days or even a few weeks) should be considered.
- Temporary soil vapor (including post-run tubing) and sub-slab vapor probes should be allowed to equilibrate for a minimum of two hours.

Soil vapor well installation methods and equilibration times should be recorded in the field logbook or a field form. For further details about equilibration times, refer to the **Soil Vapor Probe Installation Toolbox Fact Sheet**.

7.3.5. Passive Soil Vapor Probes

Several passive soil vapor sampling devices are commercially available. The installation procedures depend on the specific device, but common installation/deployment methods include burial of the sampler in a small-diameter borehole drilled using a rotohammer drill with a 1- to 3-ft drill bit, deployment in a new or existing well, and burial of the sampler in a shallow hand-dug hole. Examples of proper passive soil vapor probe installations are shown in **Figure 7-21** below. Practitioners should confirm with their local regulatory agency whether passive soil vapor sampling is acceptable for their project, and if so, what the data can be used for (i.e., plume characterization versus risk assessment). Additional details about passive soil vapor sampling methods can be found in **Section 7.4.2**. For more information on the proper installation/deployment and use of several passive soil vapor sampling devices, refer to ITRC's *Passive Sampling Technology Guidance* (ITRC 2024).



Note: PSG = passive soil gas.

Figure 7-21. Diagram (left) and photograph (right) of a typical passive soil vapor probe.

Source: Beacon Environmental, used with permission.

7.4. Sampling Methods

Evaluating a site for a potential VI concern typically includes field investigations where media samples are collected. The primary media that are sampled are soil vapor, sub-slab vapor, and indoor/outdoor air (and crawl-space samples to a lesser degree). These media samples can be collected using either active or passive sampling technologies from the sampling points described in **Section 7.3**. Both practitioners and regulators can refer to the **Reviewing Soil Vapor Data Checklist** during sampling activities to ensure that samples are being collected properly. The following subsections provide details on both active and passive sampling methodologies for the abovementioned media.

Other media, such as soil, groundwater, or NAPL, may be sampled as part of a VI investigation. Additional details about sampling these media are presented in **Section 7.6** of this document.

7.4.1. Active Sampling Methods

Active sampling uses a pump or the vacuum of an evacuated canister to collect air or vapor either inside a sampling vessel or onto an adsorbent. For indoor/outdoor air, the sample is pulled from the surrounding air at a specific sampling location. For soil vapor and sub-slab vapor, the sample is withdrawn from the

subsurface. These methods give concentration data (e.g., µg/m^3), which can be directly compared to risk-based screening levels or used in predictive models. When using active sampling methods, media are commonly collected in stainless-steel evacuated canisters, adsorbent tubes, gas-tight air sampling bags (commonly known as Tedlar® bags), evacuated glass containers, syringes, or glass bulbs. Some of these sampling vessels are limited to specific media.

7.4.1.1. Active Sampling Collection Vessels

This section presents details about the abovementioned sampling vessels used to collect sample media during VI investigations. When using any of these vessels for collecting soil vapor and/or sub-slab vapor, purging and leak checking will be performed prior to the collection of the actual sample. Details about purging and leak checks are presented in Section 7.4.1.3 of this document.

7.4.1.1.1. Evacuated/Passivated Canisters



Figure 7-22. Examples of passivated stainless-steel canisters.

Source: H&P Mobile Geochemistry, used with permission.

The sampling canisters shown in Figure 7-22 are stainless-steel containers (commonly called SUMMA® canisters) that are passivated or specially lined and inert. Passivated canisters are the most common sampling vessel in North America for both indoor/outdoor air and soil vapor/sub-slab vapor. The two most common sizes are 1-liter (L) and 6-L canisters. These canisters, which are typically provided to the sampler by the laboratory, are sent to the field for sample collection under vacuum and certified clean and leak free. It is strongly recommended to use canisters with dedicated vacuum gauges. Prior to sampling, check the canister to ensure that sufficient vacuum is present. Laboratories typically place a vacuum of approximately 28 to 30 inches mercury (Hg) on the canisters prior to shipment to the site. Field gauges typically have an accuracy of +/-5 pounds per square inch gauge, so field readings may differ from vacuum reported by the laboratory. Additionally, sampling at altitude may impact field gauge readings (that is, for each 1,000 feet of elevation gain, the gauge may decrease by 1 inch Hg. For example, a canister reading 30 inches Hg at sea level may have a vacuum reading of 25 inches Hg at 5,000 feet). Practitioners can consider using an independent National Institute of Standards and Technology–traceable vacuum gauge to test canisters prior to and following sample collection. Any canisters with less than 25 to 27 inches Hg (depending on the state) should be replaced and not used for sample collection. Practitioners should notify the laboratory if sampling is to be conducted at a different altitude than the laboratory itself.

The canister fills with vapor/air at a fixed flow rate over a preset time period using a flow controller that is set and calibrated in the laboratory to allow controlled decrease of the internal vacuum. Canisters can be used to collect grab samples without the use of a flow controller; however federal guidance states that time-integrated samples should be collected to quantitatively assess VI (USEPA OUST 2015). Initial and final vacuums are recorded for each canister before and after deployment, typically both on the canisters themselves and the chain of custody. To ensure the canisters are filling at the proper rate, they should be routinely checked after deployment until sample collection is complete, particularly during longer periods of sampling (e.g., 24 hours). Flow controllers can also be altered during transport, so it is good practice to confirm prior to use. The canister must be retrieved prior to being completely filled; it is typically recommended that sample collection is stopped with a remaining vacuum of around 5 inches Hg. Moisture can adversely affect both the sample quality and canister's interior, so efforts should be made to avoid intake of water into the canister. When collecting duplicate samples, the laboratory should provide tee-fittings that facilitate the simultaneous collection of multiple canisters in one location. Canisters should not be cooled or left in the direct sunlight during storage or transport for analysis.

For indoor/outdoor air, the laboratory typically inspects each canister to ensure cleanliness and vacuum (known as *individually certified*). For soil vapor and/or sub-slab vapor sampling, it is more common for a percentage of the canisters to be certified by the laboratory (known as *batch certified*). For high-profile projects (e.g., those potentially resulting in litigation), individually certified canisters may be recommended for all media to avoid potential for carry-over from prior use.

When used for indoor/outdoor air, soil vapor, and sub or sub-slab vapor sampling, various leak tests will be conducted on the sample tubing and its connections (known as the *sample train*). When performing these leak tests, the canister should be connected to the sample train and kept closed until sample collection begins. Practitioners should ensure that the canisters remain closed while any leak-check compound is applied. For more information about purging and leak checks, refer to **Section 7.4.1.3** of this document.

Advantages of collecting media samples in passivated canisters include the capability of analyzing multiple samples from the same canister and the ease of deployment and retrieval. Additionally, advances in flow controller technology now allow for samples to be reliably collected in canisters over a longer period of time (e.g., two weeks; Rossner et al. 2024). Disadvantages of using passivated canisters include the potential for faulty flow controllers and/or connections, potential for theft if not secured, and a lack of public awareness regarding the canister's purpose.

7.4.1.1.2. Sorbent Tube Sampling



Figure 7-23. The left photograph shows examples of sorbent tubes used to collect air and vapor samples. The middle and right photographs show a TO-17 sorbent tube being sampled using a syringe and low-flow air pump, respectively.

Source: James Walden (left); Beacon Environmental (middle); California Department of Toxic Substances Control (right), used with permission.

Sample collection on an absorbent can be done actively or passively. Sorbent sampling is an option for VFCs, but it is a requirement for the analysis for SVOCs and some TPH speciation. Examples of various sorbent tubes are shown in **Figure 7-23**. Active sorbent tube sampling requires drawing air/vapor at a calibrated flow rate through a tube containing adsorbent media over a specified time. For air sampling, the sorbent tube is connected to a pump that pulls in air at a chosen flow rate. For vapor sampling, the adsorbent tube is connected between the probe and a low-flow pump or syringe so that the pump/syringe

pulls the vapor through the adsorbent. When using a low-flow pump, the pump should not be placed upstream of the adsorbent to avoid cross-contamination between samples. Pump flows should be measured with a calibrated meter before and after use to ensure correct and documented measurement of volumetric flow and the total volume sampled. Also, the pump flow rate when sampling vapor might change if the soil permeability changes; therefore, a constant pressure controller is recommended to be used when sampling soil vapor to provide pressure regulation.

The laboratory should provide guidance on the type of adsorbent, flow rates, and required volume for the VFCs of interest. The flow rate and sampling volume used are determined based on the chosen adsorbent, the VFCs, and the amount (mass) of adsorbent contained in the tube. The samples are transported to the laboratory for thermal or chemical desorption and subsequent analysis. Reporting limits are based upon the amount of air/vapor that is passed through the tube and the method detection limit for each compound. Coordination with the analytical laboratory is important as different sorbent tubes have different flow rates for sample collection (Table 7-3).

Table 7-3. Flow rates for sorbent tubes based on analytical method.

Method	Analytes	Sample Flow Rate
TO-4A	polychlorinated biphenyls (PCBs)	225 liters per minute (L/min)
TO-10A	pesticides and polychlorinated biphenyls (PCBs)	1–5 L/min
TO-13A	polycyclic aromatic hydrocarbons (PAHs)	225 L/min
TO-17	volatile organic compounds (VOCs) / semivolatile organic compounds (SVOCs) / total petroleum hydrocarbons (TPHs) / per- and polyfluoroalkyl substances (PFAS)*	0.010–200 milliliters per minute (ml/min)
NIOSH 6009	mercury	150–250 ml/min

*A modified version of TO-17 is used for the analysis of PFAS.

For soil vapor or sub-slab vapor sampling, some regulatory agencies require applied vacuums on the vapor probe to be less than 10 to 12 inches of Hg (100 inches water) and a flow rate less than 200 milliliters per minute (mL/min) (California DTSC 2015).

When elevated concentrations of VFCs are anticipated, it is common to use two tubes that are placed in series in case there is any breakthrough of the VFCs from the first tube. An alternative approach is to collect two individual tubes at each sampling location: one sample at the laboratory recommended sample volume to reach the detection limits and a second sample collected at 10% of the laboratory recommended sample volume. The lower volume sample is then available for analysis if the higher volume sample is saturated by VFCs. The sample volumes might be adjusted downward if high concentrations are expected or detected at the sampling location.

As with passivated canisters, various leak checks should be performed on the sample train when using sorbent tubes to sample soil vapor and/or sub-slab vapor. The sample train should include a valve that allows the sorbent tube to be closed off during the purging process. For more information about purging and leak checks, refer to Section 7.4.1.3 of this document.

It is important to use a sorbent that is certified clean and that can be reliably used for the collection and analysis of the VFCs. After sampling, the tubes are sealed and transferred to the laboratory in the supplied sample container; when using multi-bed sorbent tubes, they are stored and transported with ice packs in an insulated box. Most sorbent tubes do not require storage or transport of tubes below ambient temperatures.

Advantages of using sorbent sampling include a larger number of applicable analytical methods, costs, and the commercial availability of a variety of different sorbent materials. A limitation of sorbent sampling is the risk of potential compound breakthrough with active sampling and the additional QC checks that may be required to ensure breakthrough did not occur if high ppmv concentrations are anticipated. In addition, compounds in soil vapor with low health-based criteria may require long sampling durations to achieve required detection limits.

7.4.1.1.3. Active Sample Collection into Gas-Tight Air Sampling Bags

The two most commonly used air sampling bags are commonly known as Tedlar® and Kynar® bags. A Tedlar® bag is a gas-tight bag made from polyvinyl fluoride film that comes in multiple sizes (e.g., 1-L and 6-L sizes). A Kynar® bag is an airtight sampling bag made from polyvinylidene (PVDF) and also comes in multiple sizes (e.g., 1-L and 5-L sizes. Both bags are made with a polypropylene/ polytetrafluoroethylene sample port on the front that allows it to be filled when open and gas tight when closed. Air sampling bags are commonly used to collect soil vapor and/or sub-slab vapor samples but not typically used to collect indoor or outdoor air. Note that PVDF bags may be more appropriate when lower reporting limits are desired.



Figure 7-24. Filling a Tedlar® bag using a syringe and three-way valve (top left); filling a Tedlar® bag using a vacuum chamber (sometimes called a lung-box; top right); a black Tedlar® bag, often used for sampling vapors that may be affected by light (bottom left); and a Kynar® bag (bottom right).

Source: H&P Mobile Geochemistry.

After purging and application of the leak detection compound over the probe, soil vapor can easily be transferred from the soil vapor probe into an air sampling bag using a syringe. Other devices such as a vacuum chamber (available from SKC, Inc. and other vendors) can also be used to fill air sampling bags,

but pumps upstream of the air sampling bag should not be used because cross-contamination between samples will occur. The syringe and pump methods are shown in Figure 7-24. The air sampling bag should be filled, while being careful not to overinflate and potentially compromise the bag seals.

Using air sampling bags offers the advantage of testing the actual soil vapor sample that will be later analyzed for VFCs for the leak detection compound (this is not possible with canisters as described previously). The chosen portable meter can be connected directly to the air sampling bag to measure the tracer compound or various field parameters like total VOCs, methane, O_2, etc. If the tracer compound is below acceptable levels, then the soil vapor sample is valid, and the remaining amount in the air sampling bag can be sent for analysis.



Figure 7-25. Transferring soil vapor sample from an air sampling bag into a 400 cc canister. The photograph on the right is a close-up image of the one on the left.

Source: H&P Mobile Geochemistry.

Storage (hold) time for air sampling bags is approximately 48 hours for VOCs and most aerobically degradable compounds because VFCs can plate out or bind to the walls of the sampler or otherwise be released from the bag, resulting in loss of analyte and compromise of the result. As such, it is more common to see them used for sampling SVE systems and/or in tandem with a mobile laboratory. Note that some states allow a hold time of up to 72 hours for air sampling bags. Air sampling bags are generally not suitable for naphthalene. Not all air sampling bags are the same, however, so use a bag that has been shown by the manufacturer or the laboratory to be stable for the chemicals of interest. Care must be taken to not puncture or compress the bag during storage. The bags should never be chilled. If storage times longer than 48 hours are anticipated, or if a more durable storage container is desired, the sample in the air sampling bag can easily be transferred into a passivated canister (see Figure 7-25). This is something that should be anticipated prior to mobilizing to collect samples. Air sampling bags can be subject to photodegradation, so avoid direct sunlight during sampling and shipping activities to maintain data integrity (USEPA, Method 40; USEPA Method 18; California Air Resources Board Method 422). It is also good practice to use opaque containers to store the air sampling bags both before and after sample collection.

7.4.1.1.4. Active Sample Collection into Gas-Tight Glass Containers

Gas-tight glass vials and glass containers with valves or stopcocks can also be used for sample collection. Examples of glass containers are shown in Figure 7-26. Prior to sampling, the gas-tight vial should be evacuated to a vacuum of approximately 26 to 30 inches Hg. This can be easily done with an electric vacuum pump or with a hand vacuum pump that is typically available at automotive part stores (they are used for automotive brake repairs). A soil vapor sample is withdrawn using a syringe as described previously, except that a needle is placed on one side of the three-way plastic Luer valve. The

needle is pushed through the rubber septum on the evacuated vial, and the soil vapor sample is pushed into the vial. The vial is typically over-pressured by adding a volume larger than the vial volume.

An evacuated glass container with a valve (BottleVac) is commercially available. This unit is filled similarly to an evacuated metal container. Glass bulbs are generally filled by allowing the soil vapor to flow through the bulb and closing the stopcocks on each end.

Since it is difficult to perform these sampling procedures under a shroud, leak detection is best done by performing a shut-in test on the sample train and then covering the probe with a small shroud or towel containing the leak detection compound (leak test method 1). The soil vapor is tested for the leak detection compound before and after collecting the sample as described previously for canisters.



Figure 7-26. Gas-tight evacuated glass containers.

Source: Entech Instruments, Inc, used with permission.

7.4.1.1.5. Active Sample Collection into Syringes or Glass Bulbs

Several state agencies allow soil vapor sample collection and analysis by a mobile laboratory. Typically, these samples are collected in a syringe and/or glass bulb. Examples of mobile laboratories and acceptable syringes are shown in Figure 7-27. When collecting a sample in a syringe or glass bulb, the field personnel should first complete a shut-in test as described in Section 7.4.1.3.3.1. Following the successful completion of the shut-in test, the probes should be leak tested using the liquid/solid compound leak-check method, as described in Section 7.4.1.3.3.2. Following the leak check/purge, the field personnel will close the valve to the pump, open the side connected to the syringe/glass bulb, and draw in the sample by hand. The field personnel must be cautious to draw in the sample at a steady rate that does not exceed 200 mL/min.



Figure 7-27. Examples of glass syringes used to collect soil vapor samples, often for analysis on a mobile laboratory (left) and a soil vapor sample being collected in a syringe (right).

Source: H&P Mobile Geochemistry, used with permission.

Hold times for samples that are collected in syringes and glass bulbs are short. Therefore, these samples should be analyzed by the mobile laboratory as soon as possible and not be transported to a fixed laboratory. Until analyzed, samples that have been collected in syringes and glass bulbs should be kept in a cool, dark location, such as a cooler without ice, to protect them from exposure to light. Exposure to high heat can cause compound degradation and leakage from the syringe or glass bulb, while cold can cause moisture condensation, which can affect analyte recovery. Should a sample be exposed to extreme temperatures, it should be discarded, and the probe resampled.

7.4.1.1.6. Sample Collection in Extreme Weather

Extreme weather conditions (i.e., temperatures above 85°F or below 32°F and/or heavy rain or snow) can introduce many unexpected complications during sampling activities. If field personnel must sample under these conditions, proper precautions should be taken. Below are some examples of the precautions that should be considered to ensure sample integrity:

- Be prepared for any potential extreme weather conditions (check forecasts in advance).
- Determine whether ambient temperatures will affect sample collection (e.g., sample volume issues).
- Store sample collection equipment in a temperature-controlled environment in between use at a designated sampling location. During extreme heat, ensure that the equipment does not overheat. When sampling in extreme cold, equipment should remain in a heated area (e.g., inside a field vehicle) until immediately before use. When sampling in extreme cold, pumps, motors, and/or diaphragms should be warmed up before pulling/pushing samples.
- Ensure that electronic displays are not exposed to extreme cold or the sun, as these conditions may cause them to distort or pixelate.
- Ensure that field personnel have sufficient batteries for sampling equipment. In extreme cold, some batteries may not produce sufficient voltage. In extreme heat, batteries may overheat. When sampling in extreme temperatures, field personnel may want to consider single-use lithium batteries when possible. In practice, single-use lithium batteries seem to offer the best low-temperature performance.
- In extreme cold, o-rings may shrink or stiffen, which may result in leaks and/or sample dilution due to inadequate seals.
- Consider using portable coverings or shelters such as ice fishing tents or easy-up tents. These may reduce exposure to sun, wind, snow, and rain without impeding ground access.
- When sampling in extreme temperatures, consider storing samples in a temperature-controlled container. Keep in mind that coolers are just temperature insulators and can be used to keep samples and equipment warm as well as cool. In extreme cold, personnel can place inexpensive disposable hand warmers within a cooler. In extreme heat, blue ice can be used to keep samples cool without adding moisture.
- In extreme cold, field personnel should ensure that they keep their hands warm.
- Many states have guidelines for sampling during or after significant rain events. For example, California's Active Soil Gas Advisory states that soil vapor sampling should not occur during a significant rain event, which is defined as ½ inch or greater of rainfall during a 24-hour period (California DTSC 2015). Furthermore, states may require a waiting period following a significant rain event. These waiting periods may be determined based on drainage curves (California DTSC 2015).
- Extreme barometric pressure fluctuations may lead to the introduction of atmospheric air into the vadose zone. Studies have shown that sample collection during elevated or rising barometric

pressure can result in an underestimation of VFC concentrations in indoor air (Kram et al. 2020). Some states may recommend that sampling events be delayed until frontal systems have passed the area (California DTSC 2015).

7.4.1.2. Active Indoor/Outdoor and Crawl-Space Sampling

Active indoor/outdoor samples are primarily collected in passivated canisters and sorbent tubes with a pump. Unlike when sampling soil vapor/sub-slab vapor, these samples do not require purging prior to sample collection; however, there is a leak/vacuum check a practitioner can use when collecting an air sample using an evacuated canister. To complete this check, the cap is removed from the canister, a clean vacuum gauge is attached, and the valve is opened (Figure 7-28). The gauge should read the vacuum inside the canister and remain steady. If the vacuum is too low (i.e., <25 inches Hg), the practitioner may consider removing that canister from use. If the vacuum drops, then there may be an issue with the connection. The sampling vessels are placed in the desired location, as explained in Sections 7.3.1 and 7.3.2 and either the canisters are opened, or the pump is turned on. As presented in Sections 7.4.1.1.1 and 7.4.1.1.2, the desired volume of air is then collected at a specified and predetermined flow rate. Field personnel should periodically check the canisters during the sampling period to ensure the sample is being collected at the appropriate flow rate.



Figure 7-28. Leak checking an evacuated canister prior to collecting an indoor/outdoor air sample.

Sources: Enthalpy Analytical (left) and H&P Mobile Geochemistry (right), used with permission.

When sampling indoor or outdoor air into sorbent tubes, a pump will be necessary to collect the sample, as shown in Figure 7-29. Practitioners should ensure that the pump is properly set to the required flow rate and routinely check the samples in case the pump dies or faults. It is good practice to have extra pumps and/or batteries for the sampling event.



Figure 7-29. Active outdoor (left) and indoor (right) air sample being collected using a pump and sorbent tube.

Source: Beacon Environmental (left); Enthalpy Analytical (right).

7.4.1.3. Active Soil Vapor and Sub-Slab Vapor Sampling

Soil vapor sampling is the preferred sampling and investigative tool for most VI investigations. Unlike active air sampling, active soil vapor sampling involves purging and leak checks to ensure that representative samples are collected. The quality of soil vapor data depends greatly on the collection protocols. The overview presented in the following subsections attempts to identify purging and leak-check alternatives, express advantages and disadvantages, and provide appropriate flexibility and cautions where warranted by the current available knowledge and experience. A list summarizing some of the key QA/QC issues is provided in **Section 7.10**. Sub-slab vapor and interior soil vapor sampling should always be completed after indoor air sampling when both are included in the scope of work.

7.4.1.3.1. Soil Vapor Purging

The sample collection equipment used for soil vapor surveys has an internal volume that is filled with air or some other inert gas prior to insertion into the ground. This internal volume, often called the dead volume, must be completely purged and filled with soil vapor to ensure that a representative soil vapor sample is collected. If tubing is installed and sampled the same day as installation, the air volume of the sand pack should also be included in the total system volume. Probe purging is typically accomplished using a pump or a syringe equipped with a three-way valve, as shown in **Figure 7-30**. Syringes are an inexpensive and simple approach for purging small volumes up to 1 L. For larger purge volumes, a pump with variable flow rates and a flowmeter is more efficient.

Sampling assemblies (such as connecting tubing, fittings, gauges, and flow controllers) should be confirmed to be clean prior to performing any leak testing and/or sample collection (including equipment/field blanks). If reusing sample train components, they should be properly cleaned between soil vapor samples; however, sample tubing should generally not be reused.



Figure 7-30. Purging a probe with a low-flow air pump (left) and a plastic syringe (right).

Source: California Department of Toxic Substances Control (left); H&P Mobile Geochemistry (right).

7.4.1.3.1.1. Volumetric Purging

The dead volume, or stagnant air inside soil vapor probes, sand pack, and sampling trains must be purged prior to sample collection. While it is important to collect enough vapor to purge the system, collecting too much vapor may have drawbacks. The larger the quantity of soil vapor withdrawn, the greater the potential that atmospheric air might be drawn into the probe, especially when sampling at shallow depths (less than 3 feet). For sub-slab probes, purging large volumes of soil vapor have shown limited variability (Luo et al. 2009). Sampling equipment with small internal dead volumes may offer advantages over systems with larger dead volumes because the former systems require significantly less vapor to be withdrawn when purging the system (Schumacher et al. 2016). Reliable samples can be collected with the latter, especially when the probes are deeper than 5 feet.

The equation below can be used to calculate one purge volume. Three to four purge volumes are recommended as a minimum value in most states; however, some agencies define the number of purge volumes in their guidance. Since soil vapor data are often interpreted in a relative fashion, it is important that the number of purge volumes be consistent for all samples collected at the same depth from the same site (or potion of a larger site). Larger purge volumes may result in a more integrated soil vapor concentration under some conditions, provided the concentration versus purge volume is assessed using handheld meters (PID, FID, O_2, carbon dioxide [CO_2]) or a mobile laboratory.

$$V_p = V_i + V_s + V_b$$

V_p = purge volume
V_i = internal volume of tubing and probe implant
V_s = volume of the void space in the sand pack around the probe
V_b = volume of the void space in the dry bentonite in the annular space around the tubing

7.4.1.3.1.2. Indicator Stabilization Purging

While volumetric purging is used more commonly, an alternative method includes purging the soil vapor probe until indicator parameters have stabilized. The indicator stabilization method relies on the use of a multi-gas meter capable of measuring total VOCs, O_2, methane (CH_4) and/or LEL. To use this method, soil vapor must be extracted from the probe using a pump or syringe. The extracted vapor should be collected directly into an air sampling bag. The multi-gas meter is then connected to the air sampling bag to collect the applicable readings. The probe is considered purged and ready to be sampled once the parameters are stable (e.g., three readings in a row with readings that are within 30% of each other). When using this

technique, stable readings should typically not be equivalent to atmospheric conditions. The stabilization parameter(s) used should be documented on sample collection forms. When using this method for low-flow sampling, never connect the multi-gas meter to the probe, as the meter's pump flow rate is too high. The indicator stabilization purge method is not accepted in every state, so practitioners should confirm its acceptability with the applicable state or federal regulatory agency.

7.4.1.3.2. Flow Rate and Applied Vacuum

To minimize the potential desorption of contaminants from the soil, soil vapor samples should be collected using techniques that minimize the flow of soil vapor and the vacuum applied to the soil. Higher vacuums also increase the potential for leaks in the sampling system. Some regulatory agencies require applied vacuums on the probe to be less than 10 to 12 inches of Hg (100 inches water) and a flow rate less than 200 mL/min, as shown in **Figure 7-31** (California DTSC 2015).



Figure 7-31. The photograph on the left shows soil vapor being purged at 200 mL/min. The photograph on the right shows a soil vapor sample being collected with a vacuum gauge between the probe and the sample container.

Source: California Department of Toxic Substances Control (left); Enthalpy Analytical (right), used with permission.

Limiting the flow rate may not be necessary in soils permeable enough to maintain vacuums less than 15% of atmospheric pressure (about 5 inches of Hg, 60 inches of water). Studies at a site contaminated with aerobically degradable compounds that have measured soil vapor concentrations over different flow rates, ranging from 100 mL/min to 100 L/min (McAlary and Cramer 2006; USEPA 2007; 2010). No significant differences in measured concentration were observed, which suggests that flow rate does not appear to be an important variable for soil vapor concentration in coarse-grained soils.

A simple qualitative method is typically all that is necessary to estimate whether there is little permeability and whether too much vacuum is likely to be created during sampling. To do this, one can simply connect a 20 to 50 cc gas-tight syringe to the probe and pull on the plunger. If the plunger can be pulled easily, there is high permeability, and the applied vacuum will likely be small. If the plunger is hard to pull (compared to pulling outside air) or if the plunger retracts toward the probe after being released, then there is likely too little permeability to obtain an uncompromised sample. Alternatively, the pneumatic conductivity of the soil can be calculated by measuring the probe-applied vacuum at a series of extraction flow rates (e.g., 100 ml/min, 200 ml/min, and 500 ml/min; Johnson et al. 1990).

For low-permeability soils (e.g., silts), a quantitative method is preferable using a vacuum gauge placed between the probe and sample container. If canisters are being used to collect the soil vapor sample, be aware that a gauge on the SUMMA canister measures the vacuum in the canister, not the vacuum applied to the soil vapor probe. Therefore, an additional gauge must be placed in the sampling train between the flow regulator on the canister and the probe (see **Figure 7-31**). For gauges located on the flow restrictors,

check with the supplying laboratory to determine whether they measure the vacuum in the canister or vacuum at the probe tip. Vacuum reading should be recorded on a sampling log sheet and compared to specifications set by the oversight agency (typically less than 10 inches of Hg).

7.4.1.3.3. Leak Tests

Leaks in the sampling train or leaks of air into the probe tubing can result in diluting the soil vapor samples with air and will result in underestimating actual contaminant concentrations in subsurface soil vapor. Therefore, leak testing the system as a quality assurance measure is strongly recommended when quantitative soil vapor data are desired (e.g., for risk assessments). Leak testing is required by many state agencies. Note that excessive vacuum conditions resulting from low porosity soils or high moisture content soils may exacerbate the potential for air leakage.

Leak testing is recommended to be performed in two stages: (1) a *shut-in test* of the sampling train and (2) the application of a leak detection compound to the vapor probe at the surface during purging.

7.4.1.3.3.1. Shut-in Test

The shut-in test, also known as a *vacuum leak check* or *vacuum leak test*, is performed by sealing the sampling train between the vapor probe tubing termination and the sample container (such as a SUMMA canister or air sampling bag) and applying a vacuum to the sampling train. The applied vacuum should hold steady (not decrease) for at least 30 seconds. The start and end vacuum should be recorded and reported. It is good practice to use gauges that increase/decrease by an increment of one or a digital manometer with only one decimal place, as those with smaller increments may make it harder to pass the shut-in test.

Figure 7-32 shows examples of a simple sampling train arrangement for a shut-in test. The system consists of a two-way valve at the vapor probe termination, a vacuum gauge, and a three-way valve on a gas-tight syringe. The two-way valve is closed. A vacuum is then applied by drawing back the syringe plunger, and the three-way valve is turned to shut off the syringe. The vacuum in the sampling train is then monitored for at least 30 seconds. If the sampling train does not hold the vacuum, then all connections should be rechecked and the shut-in test repeated.



Figure 7-32. The left photograph shows a simple sampling train arrangement for a shut-in test using a syringe as the vacuum source. The right photograph shows a typical sampling train arrangement for a shut-in test when using a low-flow air pump as the vacuum source.

Source: H&P Mobile Geochemistry (left); California Department of Toxic Substances Control (right); used with permission.

A shut-in test can be performed on the sample train after attachment to the soil vapor probe tubing. When doing so, an additional two-way valve should be installed between the end of the soil vapor probe tubing and the beginning of the sample train. During the shut-in test, the valve should be closed.

7.4.1.3.3.2. Leak Checks Using Tracer Compounds

For the second leak testing stage, a leak detection compound is applied at or around the soil vapor probe or the entire sample train at the surface. This can be completed in one of two ways.

1. **A solid or liquid applied at the surface:** Once the shut-in test has been successfully completed, a leak-check compound that contains detectable vapors is applied at the surface completion of the probe. The leak-check compound can be applied by wetting a towel with a liquid compound (such as isopropanol, 1,1-difluoroethane, hexane, or pentane) and placing it around the probe tubing at the ground surface (Figure 7-33). Similarly, a solid compound, such as canned shaving cream, can be put in an open baggie which is then placed next to the soil vapor probe. The liquid compound should not be applied directly to the probe or any part of the sample train. A small shroud can be placed over the surface completion when purging during high winds. The sample will be analyzed for the tracer compound by the laboratory. If a water dam is used (Section 7.4.1.3.4.1), place a pool of water around the probe and watch for changes in the water level. Refer to Appendix J, Section 5.2, in the New Jersey guidance (NJDEP 2021) for more details on this method. Advantages of using a liquid or solid leak-check compound are ease of use and shorter procedural time. Disadvantages include not being able to identify a leak in real time during sampling, the potential for creating a leak when using the towel method, and the difficulty in determining a leak rate (i.e., only getting a yes/no answer to whether a leak may exist).



Figure 7-33. Performing a leak check on a soil vapor probe and sampling train using a liquid leak-check compound. Note the leak-check compound is in a baggie and placed next to the probe and sampling train at the ground surface.

Source: California Department of Toxic Substances Control, used with permission.

2. **A gaseous tracer applied to a shroud**: Once the shut-in test has been successfully completed, a shroud is then placed over the entire sampling apparatus, which is then filled with a gaseous tracer, such as helium (Figure 7-34 and Figure 7-35). It is important that the entire sampling apparatus, including sample container, all tubing and connections, and the vapor probe surface completion, are contained within the shroud. Once the leak detection compound is applied, an aliquot of the soil vapor should be tested for the tracer compound before opening the canister. If the leak detection

compound is below acceptable levels, the canister can then safely be opened. If the leak detection compound is above acceptable levels, the canister is not opened, is disconnected, and the source of the leak is found and corrected. Throughout the purge test and sampling period, field personnel should make sure to maintain a minimum volume of the leak compound in the shroud (e.g., 20% for helium). Using this procedure avoids filling canisters with soil vapor samples that fail the leak detection test. If the sample depth is very close to the surface with no surface cover/pavement, the leak-check compound may move through the soil to the sample depth. Under these scenarios, a plastic sheet can be placed on the soil surface to limit the short-circuiting of tracer gas. In some scenarios, if concerns of a leak occurring due to larger purge or sample volumes, the soil vapor probe can be retested for the leak detection compound after the canister is filled. It can be reasonably presumed that if the vapor probe and sample train are leak free after the canister is filled, the sample in the canister is leak free also. Disadvantages of this method are that it requires additional gaseous tracer, and it is difficult to turn on, turn off, and adjust the collection device once it is under the shroud. Additionally, many field helium detectors also respond to methane, so false positives can occur. Alternatively, if there is concern about atmospheric leakage through the soil matrix during sample collection, the collected canister sample can be analyzed by the laboratory for the tracer compound (e.g., helium analysis).



Figure 7-34. The top photographs show examples of a laboratory-built soil vapor sampling shroud. The bottom photograph shows a field-constructed gas shroud over a soil vapor probe and sampling train. The system consists of shroud (clear bin), helium cylinder, field helium detector, and low-flow air pump for purging.

Source: Enthalpy Analytical (top left); H&P Mobile Geochemistry (top right); California Department of Toxic Substances Control (bottom); used with permission.

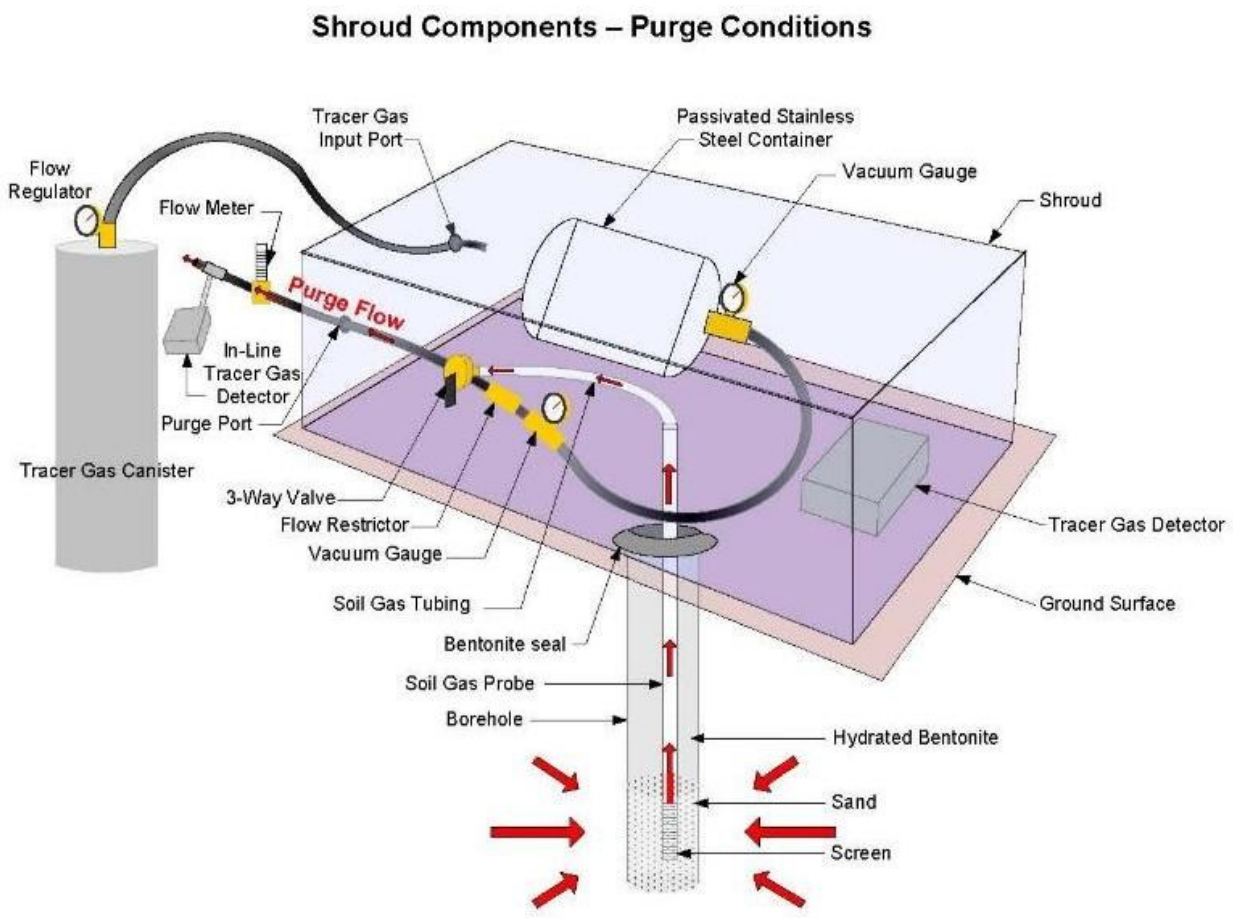


Figure 7-35. Diagram showing a proper sampling setup using a gaseous shroud.

Source: California Department of Toxic Substances Control.

Prior to collecting soil vapor samples, be sure to review any local VI sampling guidance for specific requirements for leak testing.

This video provides an overview of the process: **Soil Vapor Sample Collection with Summa Cannister**.

7.4.1.3.3.3. Testing the Soil Vapor Sample for Leaks

A small amount of tracer in a sample does not necessarily indicate an unreliable sample. For the gaseous method described above (particularly when using helium), measure both the concentration of tracer compound in the shroud and the concentration of tracer compound in the soil vapor sample in the field using a handheld field meter or with an on-site lab. If canisters are being used, measure the tracer in the probe tubing after purging and prior to opening the canister. If the tracer concentration in the probe tubing is greater than 10%–15% of the concentration in the shroud, then the leak should be found and corrected before opening the canister. Note that the procedure that indicates a leak may vary in some jurisdictions. After the canister has been filled, the probe tubing can be tested again. If the tracer concentration in the probe tubing is greater than 15% of the concentration in the shroud, then the sample in the canister may be compromised. The soil vapor sample in the canister should then be tested for the tracer at the laboratory. As previously discussed, when using this procedure, it is good practice to get your tracer compound measurement from a field sample collected in an air sampling bag. Pumps used to extract soil vapor should be limited to 200 mL per minute where guidance is required. The collected purge vapor in

the air sampling bag can also be used to measure field readings of various parameters using field meters (e.g., total VOCs using a PID, O_2, and CO_2 using a multi-gas RAE, or methane using a landfill gas meter). Fully document in the sampling log sheets both the shroud and probe tracer concentrations.

For liquid tracers, the starting concentration is either assumed to be equal to the vapor pressure of the compound at ambient temperature or can be measured if on-site analysis is available (e.g., a mobile laboratory). For liquid tracers such as isopropanol, a 10% leak would yield a concentration of approximately 10,000 µg/L in the sample, assuming a starting concentration equivalent to its vapor pressure. To account for the possibility that the starting concentration is not equal to the vapor pressure, some agencies have established a specific concentration level, such as 100 µg/L, that cannot be exceeded. This value corresponds to a 0.1% leak, assuming a starting concentration equal to the vapor pressure of the compound or a 1% leak if the starting concentration is only 10% of the vapor pressure, a conservative assumption. Other state agencies, such as the DTSC (2015, 22) state that "if the concentration of the leak-check compound is greater than or equal to 10 times the reporting limit for the target analyte(s), then corrective action is necessary." In many states, an air leak up to 5% is typically acceptable if the tracer compound will be quantitatively analyzed when using a gaseous compound and shroud, (California DTSC 2015).

7.4.1.3.3.4. Selection of Leak Detection Compound

The selection of leak detection compounds is site- and analysis-specific. Considerations include whether it is a known or suspected contaminant at the site, included in the laboratory's list of target analytes for the method being used, and/or whether it can be monitored with portable measurement devices. Common leak detection compounds are isopropanol (rubbing alcohol), helium, and fluorinated ethanes (found in duster spray cans available at most office and computer supply stores). Each of the compounds has a variety of advantages and disadvantages (Table 7-4). Always check with the laboratory regarding potential interferences from leak-check compounds.

Table 7-4. Comparison of various leak detection compounds.

Compound	Advantages	Disadvantages
Isopropanol	• Inexpensive and readily available. • Detected using methods TO-14/15/17 and SW8260. • Can be used without a shroud. • Easier to apply than other methods.	• Cannot be selectively measured in the field. • High concentrations can interfere with laboratory analysis. • Concentration introduced to sample train is only an estimation. • May leave residual contamination on sampling train. • Only provides a potential yes/no answer to whether a leak exists. • Cannot quantify a leak rate.
Helium	• Can be selectively measured in the field with a portable meter. • Will not interfere with TO-14/15/17 and SW8260 analysis. • Can quantify amount of leakage accurately.	• Party-grade helium may have low ppbv volatile organic compound contamination. • Requires additional valves, fittings, and cylinder. • Process can be more difficult than others. • False positives on meters caused by methane. • Separate analysis by TO-3A.
Fluoroethanes	• Inexpensive and readily available. • Detected using methods TO-14/15 and SW8260.	• High concentrations can interfere with laboratory analysis. • Cannot be selectively measured in the field with a portable meter.

Isopropanol is readily available, inexpensive, and does not require the use of a shroud because it can be applied to a towel placed around the vapor probe. Isopropanol can also be used with a shroud by placing the towel inside the shroud. A further advantage of isopropanol is that it can be detected using methods TO-14/15/17 or SW8260 and with a portable PID. Although isopropanol can be detected by a portable PID, the PID might be reading other compounds in the soil vapor (such as the BTEX compounds) and give a false positive. It is also possible to introduce high concentrations into the sample, which can render the sample useless by raising analytical reporting levels. When using liquid tracer compounds, take extreme care to not contaminate the sampling train parts with tracer compound. Gloves should always be worn when handling the tracer compound, and a different pair of gloves should be worn when handling/assembling sampling train components. Fluorinated ethanes are readily available and simpler to handle than helium cylinders and can be detected using methods TO-14/15/17 or SW8260. Like isopropanol, selective field meters are not readily available. When using isopropanol, potential leaks cannot be identified in real time during the actual sampling. Additionally, the laboratory results can only realistically yield a yes/no answer to whether a potential leak exists.

Helium concentrations can be readily measured in the field using a selective handheld meter. Most helium meters, such as a thermoconductivity helium detector, also respond to methane. Therefore, if methane is suspected at the site, false positives on the helium meter are possible. A further advantage of helium is that its presence in a sample, even at high concentrations, will not interfere with TO-14/15/17 or SW8260 analysis for VOCs. When using helium gas as a leak detection compound, ensure appropriate purity of the helium. Also keep in mind that the laboratory must run a separate analytical method to analyze for helium.

7.4.1.3.4. Additional Methodological Considerations for Sub-Slab Purging

Similar to sampling soil vapor probes, sub-slab sampling points should be purged prior to sampling to ensure that a representative sample can be collected for analysis. Sub-slab vapor probes typically have a much smaller purge volume (i.e., 200 to 1,000 mL). Purging is completed using a pump or syringe using either the volumetric or indicator stabilization methods presented in **Sections 7.4.1.3.1.1** and **7.4.1.3.1.2**. Prior to purging, a shut-in test should be performed as an initial leak test. During the purge process, a sub-slab vapor probe can be screened for various field measurements, such as total VOCs. To collect field measurements, as with soil vapor probes, the purged vapor should be collected into an air sampling bag and the reading taken from the bag. Field instruments, such as a PID, should not be applied directly to the sub-slab probe as their pumps typically run too fast.

7.4.1.3.4.1. Water Dam Method for Sub-Slab Probe Leak Testing

A water dam is an alternative method for testing surface seals for leaks. In this method, water is considered a leak-check compound. The water dam consists of a cylinder (e.g., a 2-inch diameter polyvinyl chloride coupling) sealed to the ground using non-VFC putty or clay. The inside of the cylinder is partially filled with water during sampling or monitoring activities. If the seal is not effective, the water will drain; therefore, visual inspection of the water level is sufficient to verify the integrity of the seal. This method does not confirm that the sample train is free from leaks and is typically used for temporary sub-slab probe sampling or screening. An example of a water dam is shown in **Figure 7-36**.



Figure 7-36. Water dam used to leak check a sub-slab vapor probe.

Source: Vapor Pin Enterprises,

7.4.1.4. Performance Monitoring for Mitigation Systems

When a VIMS is installed at a site, performance monitoring is an integral part of evaluating its effectiveness. Performance monitoring typically includes routine collection of field measurements and/or media samples for laboratory analysis. The scope and schedule for performance monitoring should be established as part of the OM&M plan, which is usually submitted to the oversight agency prior to system startup. For performance monitoring activities that involve field measurements, practitioners can use handheld devices presented in **Section 7.2.1** to collect readings of indoor/outdoor air, soil vapor and/or sub-slab vapor, vent riser air, pressure, or a system's inlet and outlet air. When performance monitoring includes the collection of media samples for laboratory analysis, practitioners can use any of the active methods presented in **Section 7.4.1**.

7.4.2. Passive Sampling Methods (TO-17 and 8260D)

Passive sampling of air and soil vapor is similar to active sampling methods in which VFCs are collected onto adsorbents; however, in passive sampling, the collection relies on the diffusion of compounds onto the adsorbent without the use of pumps or a vacuum. As a result, the measured concentrations represent natural conditions in the subsurface. Like with active sampling methods, a single analytical value is reported per sample, regardless of exposure time.

Advantages of passive samplers are their small size and lower transportation costs, and they can be easily suspended in the indoor air, outdoor air, conduits, crawl spaces, or beneath the slab to sample VFCs over a predetermined period (hours, days, or weeks). For sub-slab vapor collection, a small-diameter hole, typically less than 2 inches, is drilled through the slab to the underlying soils or subgrade material using a rotary hammer drill or concrete coring machine. The sampler is then suspended within the hole such that it sits just below the slab. A seal is then formed at the top of the slab using a form-fitting plug to prevent gases from entering or exiting the hole throughout the sampling duration and between sampling events, if applicable. In some cases, the hole can be lined with a pipe made of metal or other inert material to isolate a specific sampling depth beneath the slab. When this method is used, the pipe should be grouted in place and the sampler suspended through the pipe, which is then capped or plugged.

During deployment, VFCs diffuse onto the adsorbent at a constant rate based on Fick's law. Compounds will continue to accumulate on the adsorbent throughout the sampling duration unless the adsorbent becomes saturated. Therefore, passive samplers must contain sufficient adsorbent mass to prevent concentration equilibration. When using passive samplers to sample soil vapor, the sampling rate of the passive sampler must be less than the replenishment rate of compounds through the surrounding soil pore spaces (ASTM D7758). Thus, axial-type or permeation low uptake rate samplers are required for this type of sampling. It is recommended to consult with the laboratory regarding the sorptive capacity of the samplers offered. If the sampler becomes saturated before retrieval, the calculated concentration would be biased low. Passive samplers are designed with a large mass of sorbent that minimizes the risk of saturation, except in sampling conditions with high ppmv concentrations.

After the exposure period the sampler is sealed or placed into an airtight container until the adsorbent media is analyzed. The date and time (to the minute) of sampler deployment and retrieval are recorded on the chain-of-custody form, which is provided to the laboratory with the samplers. For risk evaluation, results for passive samplers can be reported in units of concentration (ug/m^3 or ppbv) if the uptake rates for the sampler used were validated. Note, state-specific guidance should be consulted before passive samplers are used for risk assessment purposes as the results may not be accepted by all states as definitive and final.

7.4.2.1. Sampler Types and Hydrophobic Properties

The ITRC *Passive Sampling Update* (2024) provides a description of commercially available passive samplers that are suited for sampling air and soil vapor. The main sampler designs are axial, radial and permeation types, with the axial and permeation samplers having a lower uptake rate than the radial samplers. While the relative humidity in indoor air is lower than in soil vapor or crawl spaces, adsorbents that are hydrophobic or at least have a hydrophobic membrane are recommended to protect non-hydrophobic adsorbent. As noted in ISO 16017-2, passive samplers are suitable for use in atmospheres of up to 95% relative humidity for all hydrophobic sorbents. Examples of several passive air and vapor samplers are shown in Figure 7-37 and Figure 7-38.

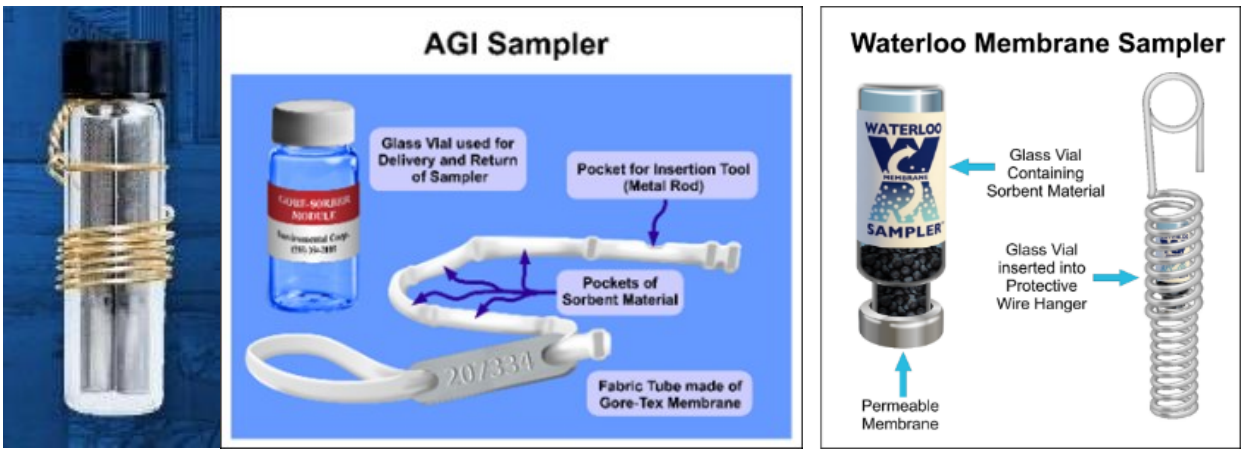


Figure 7-37. Examples of passive soil vapor samplers.

Source: ITRC (2024).

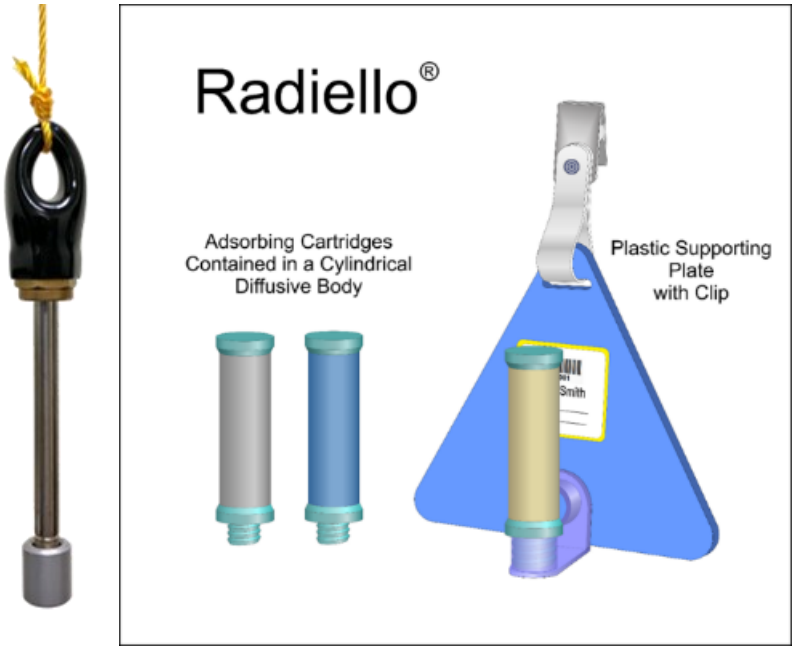


Figure 7-38. Examples of passive indoor/outdoor air samplers.

Source: Beacon Environmental, used with permission.

7.4.2.2. Sampler Analysis and Uptake Rates

The passive samplers are delivered or shipped to the laboratory without the need for ice or preservatives. Analysis of the samples is typically performed following USEPA Method TO-17 or 8260D procedures with desorption of the sample by thermal desorption or solvent extraction and analysis using GC/MS instrumentation. In general, sample introduction by thermal desorption will provide greater sensitivity and lower reporting limits than analytical methods using solvent extraction techniques. The mass of each target compound identified on the sampler is reported in units of concentration (ug/m^3) by using the following industry standard equation in ISO 16017-2 and USEPA's guidance (2014e).

$$C = M / (UR \times t)$$

Where:

C = time-weighted average air concentration (µg/m^3)
M = mass of VOC retained by passive sampler picogram (pg)
UR = uptake rate (mL/min, compound specific); also called the *sampling rate*
t = sampling duration (min)

7.4.2.3. Sampling Duration

The uptake rate (sampling rate) is the most critical variable for accurately determining compound concentrations in air when using any passive sampler (USEPA 2014d). Providers of passive samplers will have a list of uptake rates and a description of how they were determined (e.g., controlled laboratory experiments with third-party validation). The list of compounds in the study may not include all required target compounds, and the uptake rates for these compounds can be estimated using Graham's law of diffusion and the third-party validated uptake rates.

The required minimum sampling duration is determined based on the passive sampler's analytical detection limits and the required reporting limits in air for the compounds of concern using the above equation rearranged to solve for time (t).

$$t_{min} = M_{min} / C \times UR$$

Where:

t_{min} = required sampling duration (min)
M_{min} = laboratory lower reporting limit for target compound (pg)
C = soil vapor concentration required reporting limit (µg/m^3)
UR = uptake rate (mL/min, compound specific); also called *sampling rate*

7.4.3. Soil Vapor Sampling from Existing Groundwater Wells

Both active and passive soil vapor samples may be collected from appropriately screened groundwater wells, but the data generated from that sample must be considered as screening only. It may be useful in helping to refine a CSM but is rarely sufficient for final decisions. More specifically, this method is more appropriate for screening gases like methane and carbon dioxide, as opposed to other trace VFC. Wells may be screened across the water table, or the water table may have dropped below the bottom of the screen. If the well screen is only in the saturated zone, the headspace (off-gassing from impacted groundwater) will be measured rather than soil vapor. The well must either have an airtight cap and valve or an airtight packer system around tubing. Many groundwater monitoring wells have vented caps, so a retrofit may be required (**Figure 7-39**). If three to five volumes of the gas (as calculated using the well volume and either the level of water in the well or, in the case of dry wells, the bottom of the well) are purged from the well prior to sampling, the resulting gas sample should represent the gas in the vadose zone immediately outside of the well casing. For a 4-in or 6-in diameter well, the purge volume can be

significant and may introduce some error in the purging process. If the casing is not properly purged, the sample is a mixture of gas from the vadose zone, gas from the well boring, and the gas above the standing water. Field screening with portable meters can help show stability and avoid sampling error. Low concentrations of VFCs in the water can produce very high concentrations of those VFCs in the well headspace. For example, 1 ppbv of TCE in the groundwater produces a concentration of 600 ug/m^3 in the well headspace.



Figure 7-39. Collecting a soil vapor sample from an existing groundwater monitoring well.

Source: Vapor Pin Enterprises,

7.4.4. Quality Control Samples

Various blank samples are collected when sampling with both passive and active methods. Collection of equipment and field blanks are recommended for all VI investigations, especially if metal probe tips are used.

To collect an equipment blank when active sampling, zero-grade air or nitrogen should be drawn through the probe tubing, probe tip, and the sampling train at the start of the field program. The collected sample should be analyzed for the same compounds as the soil vapor samples. This practice confirms that the metal probe tips and other probe parts are clean before putting them in the ground. It is common practice to collect one equipment blank for every sampling event.

To collect a field blank when active sampling, air from the sampling location is collected into the active or passive sampler. For evacuated canisters, this involves opening the canister to collect the air (via a flow controller) and closing it once the desired amount is collected. Field blanks are rarely collected when using passivated canisters. For sorbent tubes, the practitioner typically opens the tube to expose it to the air during the sampling period.

When passive sampling, trip blanks are also commonly included in the sampling protocol. The trip blanks typically consist of an unused sampler that is kept sealed and in the shipping container during the life cycle of the investigatory process (i.e., the period including shipment from and to the laboratory). It is common practice to have at least one trip blank for each container of passive samplers.

Note that an additional QC blank sample that can be useful to VI investigations is a rinsate sample. This is a form of equipment blank that is collected during the drilling/installation process. These blanks would not be collected during the soil vapor/sub-slab vapor sampling process.

Duplicate and replicate samples are media samples collected from the same location as the primary (or parent) sample. A duplicate sample is collected from the source medium at the same time as the primary sample. A replicate sample is collected directly after the collection of the primary sample. Both are analyzed separately by the laboratory to assess the precision and variability of the sampling and analysis process. The USEPA recommends collecting one duplicate/replicate sample for every 20 primary samples; however, the frequency of duplicate/replicate collections may vary in some states. The USEPA recommends collecting field duplicate samples at a minimum frequency of 10% (one duplicate for every 10 primary) for soil, sediment, and groundwater (USEPA 2014e).

7.4.5. High-Volume Soil Vapor Sampling

High-volume sampling (HVS) of soil vapor consists of extracting and monitoring a large volume of soil vapor from beneath the floor slab of a building to provide a spatially averaged sub-slab vapor concentration. HVS is typically applied at large buildings (>8,000 cubic feet). HVS can also be completed on existing SVE wells (similar to a SVE pilot test) or a groundwater monitoring well with a sufficient screened interval above the water table to yield appreciable airflow. During HVS, slipstream grab samples are collected from the HVS apparatus and screened with field instruments (PID, O_2, CO_2, and CH_4 meter) to quantify a spatially averaged soil vapor concentration and/or evaluate a mass removal rate. Grab samples may also be collected for laboratory analysis. Further details regarding the HVS methodologies and how to use them to evaluate several physical characteristics related to VI are presented in the **High-Volume Sampling Fact Sheet**.

7.5. Sampling Locations and Frequency

7.5.1. Indoor Air

The most effective way of assessing direct exposure to VFCs is through sampling indoor air. The evaluation of indoor air data can be made more complicated due to the presence of indoor contaminant sources, elevated concentrations of VFCs in outdoor air, and changes in both the differential and barometric pressures. Contaminant sources inside a building must be considered since many commonly used household products contain target VFCs (e.g., PCE from dry-cleaned clothes, trichloroethane [TCA] from degreasing cleaners) (**Figure 7-40**) (USEPA 2024c). Outdoor air data must be considered since some VFCs (e.g., benzene) are present at concentrations exceeding allowable indoor air risk-based levels, especially in urban centers. Changes in differential and/or barometric pressures must be considered as they may increase or decrease the amount of VI that is occurring from the subsurface, which can then coincide with changes in VFC concentrations. As any (or all) of these factors could influence concentrations of VFCs inside a building, it is good practice to compare indoor air data to additional applicable information, such as ventilation status, building activity, products identified inside the target building, outdoor air concentrations, sub-slab samples with differential pressure readings, barometric pressure, and barometric pressure trends. HVAC and building activity and a product inventory can be obtained during the building survey. Outdoor air data can be obtained by performing indoor and outdoor air sampling simultaneously. Differential pressure data can be obtained by using pressure sensors at sub-slab vapor probes, while barometric pressure (and temperatures and wind speeds/directions) can be obtained from publicly available climatic data. For more information on background sources, real-time monitoring, and



Figure 7-40. Photo of bad sample placement of indoor air samples. Note the adjacent drum with liquid at the bottom.

Source: California Department of Toxic Substances Control, used with permission.

pressure monitoring, refer to the Background Sources to Indoor Air Fact Sheet, the Real-Time Monitoring Fact Sheet, and the Pressure Monitoring and Building Pressure Control Fact Sheet, respectively.

Many household items can emit VFC of potential concern (Bingham et al. 2023; Doucette et al. 2010). Prior to performing an indoor assessment, particularly for residential buildings, a comprehensive inventory of potential indoor sources of VFC should be performed, and all suspected sources removed and placed in outdoor bins. This can prove to be intrusive and time-consuming. As such, a rapid screening of areas where chemicals are stored with a handheld or mobile analytical device or system can help expedite this effort by identifying potential indoor sources. Indoor air sampling may still be the method of choice if the compound is not commonly found in household products (e.g., carbon tetrachloride, or 1,2-dichloropropane). Areas where recent home improvement activities occurred or where new furniture or carpet was installed should also be assessed. In addition, the occupants should be instructed on appropriate actions to take or avoid during the sampling event.

To address the potential impacts of climatic factors, HVAC system operations, and/or a stack effect induced by temperature change on indoor air, it is important to consider sample timing when evaluating indoor air data. All of these factors can affect how vapors move from the subsurface to inside a building. For example, indoor air data may not be indicative of normal conditions if the samples were collected when the indoor pressure was lower than the pressure in the underlying soil as a storm approached or at the tail end of a prevailing high barometric pressure event.

Temporal variability will depend on the duration of sample collection. Grab (instantaneous) samples are generally not recommended except for screening or confirming indoor sources and vapor entry locations. When using active indoor air methods, air samples are typically collected over a 24-hour period at residential properties; for commercial and industrial properties, air is typically collected over 8 hours to correspond to an average workday. The sample duration should be evaluated and agreed upon during work plan preparation. Sampling locations should be based on VFC sources in the building, suspected VI entry points, and areas where occupants spend most of their time. For example, for a residential property, it is recommended that, at a minimum, samples be placed in the bathroom, kitchen, and living room. Additional sampling locations can be added in bedrooms and other places of higher occupancy. A similar approach should be applied when sampling commercial and industrial facilities. Bathrooms, control rooms, kitchens, smaller office spaces, etc. should be carefully selected to obtain representative exposure point concentrations.

Published information on seasonal temporal variability in indoor air quality shows concentrations with a range of a factor of 2–5 for 24-hour samples (Kuehster et al. 2004; McAlary et al. 2002). Regulatory-required ventilation conditions (e.g., HVAC operation) should be confirmed prior to initiating a sampling event. Note that some states require that sampling be performed only in areas where windows and doors remain closed throughout the sampling period and air-handling systems have not been operating for several hours. Short-term temporal variability in subsurface VI can occur in response to changes in weather conditions (e.g., temperature, wind, barometric pressure trend, etc.). Short-term variability in indoor air concentrations is not generally captured in time-integrated sample results that yield a time-weighted average value. High-frequency continuous monitoring can be used to capture concentration dynamics as well as identifying controlling factors. This type of indoor data can help distinguish between indoor sources and VI and can be used to help locate vapor entry points. See the Real-Time Monitoring Fact Sheet for additional information.

Indoor air samples are typically collected after subsurface media (e.g., soil, groundwater, and/or soil vapor) sampling and/or characterization indicate the need to conduct an air quality assessment inside on- or off-site buildings. Situations that may warrant the need to collect indoor air samples before completing the subsurface soil vapor characterization include, but are not limited to, the following:

- Response to a spill event when contamination requires qualitative and/or quantitative characterization

- Screening of a building with field equipment (e.g., PID, organic vapor analyzer, or explosimeter) identify high readings, but the source is unknown
- If significant odors are present and the source is unknown
- If a building is prone to intrusion or flooding (e.g., sump pit overflows) of contaminated groundwater, and subsurface soil vapor sampling is not feasible
- A regulatory agency requires indoor air sampling
- LNAPL is present directly below the building
- DNAPL is present directly below the building
- A preferential pathway exists into the building (see CSM **Chapter 4: Conceptual Site Model, Section 4.2.16**)
- If COC have been discharged to a sewer system shared by the building or buildings in question

When performing an indoor air investigation, the analyte list used should focus on the compounds identified in subsurface samples at concentrations above applicable screening levels, the breakdown products of said compounds, and/or marker compounds that may be useful for assessing VI. Confirm the analyte list with the appropriate regulators.

7.5.2. Crawl Space / Cellar

There are several options for sampling air from the crawl space. Crawl spaces can be sampled by collecting soil vapor samples (active or passive), air samples (with canisters or adsorbents), or soil vapor samples with flux chambers. Typically, crawl-space air samples are collected following protocols similar to those for indoor air samples. The uncertainty of outdoor air contribution to a crawl space can confound analytical results, especially when crawl spaces are vented or otherwise not fully closed. It is important to search for any furnace intake components that may be located in the crawl space, as these features may also impact sample timing, location, and results. The concentration in the crawl space may be inversely proportional to the ventilation rate, which is not usually controlled. It is important to avoid sampling crawl spaces when winds are strong, to collect samples from the center of the building footprint, and to avoid sampling near crawl-space access points and vents. Flux chambers can be used to determine the surface flux of the contaminant that may be moving into the crawl space. There is little data available to assess the attenuation from crawl space to indoor air. Note that practitioners should consider any potential health and safety concerns that may arise when sampling in crawl spaces (e.g., confined spaces); refer to OSHA requirements in 29 CFR 1910.146. As an option, samples can be collected in the crawl space by inserting the probe rod or sampling tube horizontally through the crawl-space access ports or vertically through the overlying building.

7.5.3. Outdoor Air

When indoor air sampling is performed as part of a VI study, coincident outdoor air samples should also be collected. Depending on building air exchange rates, contaminants from outdoor air may make up a large percentage of indoor air contaminants. Air typically contains numerous VFCs, such as benzene, PCE, and TCE, at concentrations that often exceed those in indoor air and/or indoor air risk-based screening levels. Some compounds, however, that are not typically found in air at significant concentrations (e.g., vinyl chloride or 1,1-DCE) may be a concern for VI studies. For residential buildings, outdoor air samples should be collected from a representative upwind location, away from wind obstructions such as trees and buildings. The typical intake would be at about 3–5 feet off the ground (at the approximate midpoint of the ground level of the building) and about 5–15 feet away from the building.

For commercial buildings, outdoor air samples should be collected in representative locations for the intake(s) of the building HVAC systems. Outdoor air samples collected from multiple locations and directions are recommended when using passive or other longer duration sampling methods to account for changes in wind directions. A review of wind direction patterns may be useful when selecting sample locations.

Representative samples should be located to minimize bias toward obvious sources of VFCs (e.g., automobiles, lawnmowers, oil storage tanks, gasoline stations, and industrial facilities). Outdoor air samples should be collected and analyzed by the same method as for indoor air samples and generally for the same time periods (e.g., between 8 and 24 hours for active sampling and days to weeks for passive). Consider collecting basic meteorological data during the sampling event. It can also be prudent to sample from the HVAC air intake to make sure indoor VFC detections are not due to outdoor sources.

Practitioners should check the requirements of their local agencies. Some state agencies recommend that outdoor air samplers be deployed prior to indoor air monitoring (California DTSC 2023). This practice is recommended since most buildings have an hourly air exchange rate in the range of 0.25–1.0, and air entering the building in the period before indoor sampling may remain in the building for a long time.

7.5.4. Soil Vapor and Sub-Slab Vapor

Measurement of soil vapor is a common approach around the country for evaluating the VI pathway. Soil vapor samples provide direct measurements of subsurface vapor concentrations that can be used to verify theoretical calculations (e.g., modeling) Risk-based screening levels for soil vapor are generated by applying an AF to indoor air screening levels. Drawbacks to estimating the indoor air concentration from soil vapor data include uncertainty about the proper AF to apply. Soil vapor data are preferred over soil matrix and groundwater data because soil vapor data represent a direct measurement of the vapor-phase contaminant that can potentially migrate into indoor air.

In 2012, USEPA presented the results of VI modeling that provided insights into the spatial and temporal variability of soil vapor and indoor air data (USEPA 2012a). The document addresses various factors such as vapor source characteristics, subsurface conditions, building features, and general site conditions. The modeling considered both easily biodegradable and recalcitrant contaminants that cover typical scenarios at sites with VI concerns. The findings included recommendations for sample locations and timing to improve the reliability of VI sampling results, which are incorporated throughout the following subsections.

The two methods available to measure soil vapor contamination in the unsaturated zone are active and passive soil vapor sampling. More details about soil vapor sampling methods can be found in **Sections 7.3** and **7.4**.

Soil vapor and sub-slab vapor samples can be further differentiated laterally by their location. These include the following:

- Exterior soil vapor samples are generally collected 10 feet or more from the perimeter of the building.
- Near-slab soil vapor samples are collected outside of a building's footprint but within a short distance (often 10 feet) of its foundation.
- Interior soil vapor samples are collected from within a building footprint.
- Sub-slab vapor samples are collected from below the building foundation or concrete floor slab in contact with either native soil or base fill material (depending on building construction).

Sample collection depths for near-slab and exterior soil vapor samples should be at least 3 to 5 feet below grade to avoid impacts due to atmospheric interferences, such as potential short-circuiting or barometric pressure (Hartman 2006). Note that the depth of probe placement will depend on the thickness of the building's slab. Since sub-slab vapor probe installation requires penetrating the floor of a building, practitioners should consult with the property owner and/or occupant to minimize damage and aesthetic effects (see **Section 3.2.5 Property and Building Access**). In cases where groundwater is shallow (at 5 feet or less), groundwater samples may be collected rather than sub-slab vapor and/or shallow soil vapor samples if there is a potential to draw water into the sample collection device.

Sub-slab vapor sampling is the preferred approach of many regulatory agencies for investigating VI primarily because of the proximity of the sample location to the receptor and the reduction of background interferences (when proper sampling methods are employed).

Sub-slab vapor concentrations, by themselves, do not necessarily indicate the extent to which VI is occurring nor, if so, whether VI represents a health risk. Conversely, if the concentrations in sub-slab vapor are not higher than the applicable regulatory screening levels, there may be no further need for assessment. This principle may be a key LOE in screening a site out of additional investigatory actions and/or costly indoor air monitoring and mitigation programs (see **Chapter 5: Site Screening**). For more information on MLE, see the **Multiple Lines of Evidence Fact Sheet**. Note that while indoor air concentrations may suggest VI is not occurring for a building, high concentrations of VFCs that remain in the sub-slab may pose a VI risk in the future.

It is important to understand that assessing sub-slab vapor and/or soil vapor data may require the need to estimate indoor air concentrations using an AF. For more on AFs and methodologies for evaluating vapor data, refer to **Chapter 8: Data Evaluation and Vapor Intrusion Risk Assessment** and the **Attenuation Factors Fact Sheet**.

7.5.4.1. Soil Vapor Sampling Locations

The initial criteria to apply when determining where to collect soil vapor samples for VI assessments are the location of the contamination source relative to the building, the depth of the contamination source, and the use and construction of the building. The following sections recommend locations for collecting soil vapor samples, both laterally and vertically, for some typical situations. Additional suggestions are available from API (2005), DTSC (2015; 2023), USEPA (2023), NJDEP (2021), and ASTM (2006; 2009).

7.5.4.2. Sample Density

When subsurface contamination is encountered near buildings, soil vapor and sub-slab vapor samples are typically collected to assess the contaminant distribution in sufficient detail to identify buildings that may have unacceptable levels of VI. Characterization can be considered complete when concentrations of VFCs and/or aerobically degradable compounds meeting acceptable risk-based levels are encountered in the subsurface both laterally and vertically between the source and potential receptors. Note that lateral delineation may be challenging at some sites due to highly variable concentrations (USEPA 2012a). The exact number and spacing of samples (sample density) varies on a site-specific basis, but sufficient soil vapor and/or sub-slab vapor samples should be taken to make appropriate decisions. For smaller sites (e.g., houses surrounding a dry cleaner or a gas station), a soil vapor and/or sub-slab vapor sample should be taken for every existing or future building. At larger sites (e.g., a groundwater plume under a large neighborhood), enough samples should be collected to give sufficient spatial coverage of the area over and near the contamination. For sites where current and future land use will be restricted by a land use covenant, the soil vapor and/or sub-slab vapor sampling density can be modified as a function of the size of the current and future buildings pursuant to the covenant.

When sampling near or under individual buildings, collect enough samples to obtain a representative value of the soil vapor and/or sub-slab vapor concentration (analogous to placing enough borings on a typical site to characterize the extent and degree of contamination).

7.5.4.3. Lateral (Spatial) Sampling Locations

When determining lateral sampling locations, practitioners should always consider state and federal guidance, project DQOs, and site conditions. It is also important to consider the project's VFCs and any minimum distance requirements for site screening. For more information, refer to Step 2.1 in **Chapter 5: Site Screening**.

If the extent of the contamination is not known and future development is anticipated, then sampling points for assessing the VI pathway are located to give representative coverage of the entire site so that no contamination zones subject to vapor migration are missed. If the extent of contamination is known, then sampling points are located over the contamination zone. If the property's use is not changing and on-site buildings are not threatened, then it might be appropriate to only locate points at the property borders to ensure that no vapors are migrating off-site. When buildings exist, collect samples on the side of the building closest to the source. Collect samples in any known subsurface migration routes, such as sewers or utility line backfill, that extend toward the contamination. If concentrations exceeding screening levels are detected, next steps may include additional soil vapor sampling, proceeding to sub-slab and/or indoor air sampling, or collecting samples from sewer cleanout and/or vents.

It is important to consider the following parameters when selecting lateral sample locations:

- **Subsurface Contamination Adjacent to a Building:** If the contamination source is not directly below the building, collect samples on the side of the building closer to the source. Collect samples in any known subsurface migration routes, such as sewers or utility lines that extend toward the contamination. If concentrations exceeding screening levels are detected, it may be appropriate to proceed to sub-slab sampling.

- **Subsurface Contamination Underneath a Building:** If the contamination source is directly below the building, collect sub-slab vapor samples and/or indoor air samples. If possible, collect enough samples from multiple locations to get a representative value under the footprint of the building and attempt to colocate sub-slab vapor and indoor air sample points. Samples should be located such that spatial distribution of the contamination, potential entry pathways, and building-specific HVAC configurations are evaluated/determined. Note that this will vary from one building to another, even within a single site. When practicable, sub-slab vapor probes should be placed a minimum of 5 lateral feet from an exterior wall. If sub-slab samples are not possible, collect near-slab soil vapor samples around all sides of the building to determine the concentration distribution and get an idea of the possible concentration under the building. An alternative approach, such as HVS (Section 7.4.5) may be required for very large buildings.

- **Surface Contamination Within or Immediately Adjacent to a Building:** This situation is most likely applicable to commercial facilities with adjoining businesses (e.g., dry cleaners at strip malls) or industrial settings with partitioned or immediately adjacent buildings. The contamination enters the shallow vadose zone from the surface, as a dense vapor or as a liquid spill, and then migrates laterally underneath the building slab. Collect samples directly underneath the building slab covering the area of concern in the building.

7.5.4.4. Sampling Locations for Vertical Delineation

As with lateral sampling locations, practitioners should always consider state and federal guidance, project DQOs, and site conditions when determining vertical sampling locations/depths. It is also important to consider the project's VFCs, assess whether NAPL is present, and/or consider any minimum

distance requirements for site screening. For more information, refer to Step 2.1 in **Chapter 5: Site Screening**.

The closer a sampling probe is to the ground surface or building foundation, the greater the chance that surface processes, such as atmospheric interference, precipitation, and advective flow induced from the overlying building, will affect the soil vapor concentration. In general, the effects due to these processes are considered to be minimized at depths of 3–5 feet bgs or building foundation, and measured soil vapor concentrations are less likely to fluctuate (USEPA 2012a). Some processes, such as bioattenuation, oxygen replenishment, and barometric flushing, occur primarily at shallower depths (<3–5 feet), so sampling in this zone should not necessarily be precluded. Additionally, the construction of a new building may affect some of these processes and thus affect soil vapor concentrations. If soil vapor data from depths <3–5 feet bgs or below the level of the foundation are collected, additional sampling events may be appropriate to ensure representative values, especially if the measured values yield risks that are near acceptable levels.

Multiple-depth samples should be collected as needed to define vertical trends in soil vapor concentrations or to determine maximum concentrations at the contamination source (USEPA 2012a). Deeper samples tend to minimize temporal variations. The capillary fringe zone above the water table should be avoided if possible because high water saturation makes soil vapor sampling difficult. If groundwater at a site varies, soil vapor probes installed within the capillary fringe may become saturated resulting in low- or no-flow conditions (i.e., vapor lock), or they may pull water into the sampling vessel (which could destroy a stainless-steel evacuated canister). If groundwater at a site is shallow (5–8 feet bgs), soil types and climate/weather may play a larger role in determining whether shallow soil vapor sampling is viable. Practitioners may consider collecting groundwater samples in lieu of soil vapor, or for a site with an existing building, collecting sub-slab vapor and/or indoor air samples. Note that some states, such as California, may recommend sampling in the capillary fringe if characterization to groundwater is needed (California DTSC 2015).

Exterior soil vapor samples collected from just above the source are expected to provide a conservative estimate of sub-slab concentrations. (They are considered conservative because there is the potential for attenuation between the sampling point and the sub-slab point.)

Ultimately, sampling depths may vary from site to site. Practitioners should always consult their local regulatory oversight agency for any agency-specific guidelines. Some general recommendations regarding selection of vertical samples are provided below:

Subsurface Contamination Adjacent to a Building. Collect samples between the building and the source at about 5 feet below the lowest floor or shallower if the contamination source is shallower. For buildings with basements, at least one vertical profile along the basement wall facing the contamination source is advised.

Subsurface Contamination Underneath a Building. If accessible, collect samples immediately below the building's foundation. For hydrocarbons, collect near-building samples at about 5 feet below the lowest floor or shallower if the contamination source is shallower. For chlorinated hydrocarbons, collect samples near the source (but no deeper than the top of the capillary fringe). If concentrations exceeding screening levels are detected, either collect additional samples around the building to allow better determination of the concentration distribution around the building or proceed to interior sampling (sub-slab and/or indoor air).

Surface Contamination Within or Immediately Adjacent to Building. As described in the prior section, this situation is most likely applicable to commercial facilities with adjoining businesses (e.g., dry cleaners at strip malls) or industrial settings with partitioned or immediately adjacent buildings. Collect samples directly underneath the slab covering the area of concern in the building.

7.5.4.5. Applications of Vertical Profiling of Soil Vapor Concentrations

Vertical profiles of soil vapor concentrations can be useful for the following situations:

- Determining the source of the contamination if not previously known
- Determining the attenuation of contaminants in the soil vapor in the vadose zone due to bioattenuation or other processes

Depending on the depth of groundwater, vertical profiles should consist of a minimum of three sampling depths, fewer for shallower aquifers. If repeated data are desired, install soil vapor monitoring tubes for easy re-sampling.

7.5.4.6. Sampling Locations at Sites with Petroleum-Based Vapor-Forming Chemicals

As with all VI sites, identifying the source area(s) is a crucial step in characterizing lateral and vertical extents of impact. Sites with concerns about petroleum-based VFCs include, but are not limited to, existing or former well fields, refineries, pipelines, tank farms, and gasoline stations. When evaluating one of these sites for aerobically degradable compounds, existing or former buildings that either held, moved, or dispensed petroleum products should be targeted first as potential source areas. These may include USTs, ASTs, pipelines, production wells, and fueling pumps. If these buildings are existing, additional steps and/or requirements may be required by the facility to protect the buildings' integrity. If the source area is believed to have been a smaller isolated area, such as a truck or railcar spill, a practitioner's focus should first be on the spill area.

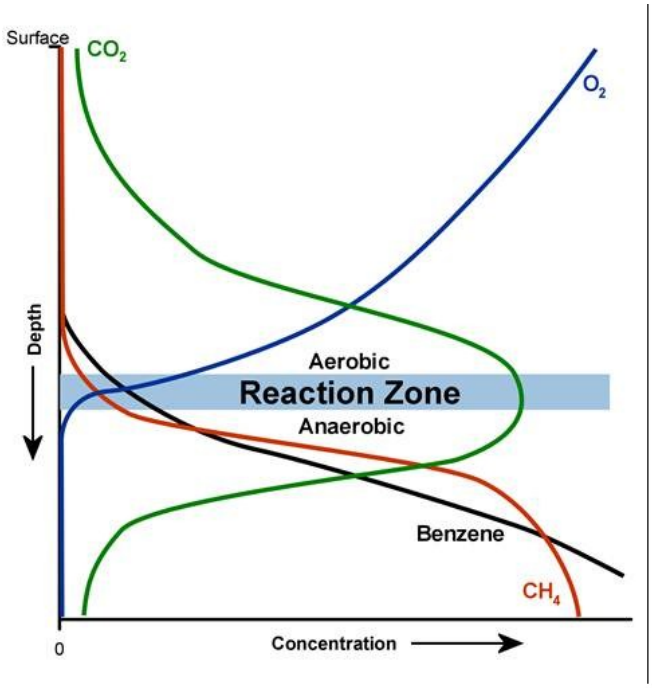


Figure 7-41. Depth versus concentration plot of O_2 and aerobically degradable compound concentrations.

Source: G.T. Ririe and R.E. Sweeney, used with permission.

At sites with petroleum-based and/or aerobic chlorinated VFCs, it is desired to document the depth of the reaction zone where conditions change from aerobic to anaerobic to determine the thickness of the aerobic vadose zone separating the contamination source from the building (USEPA 2012a). This determination can be made by conducting a vertical profile of soil vapor concentrations using field tools to screen for the presence of VFCs, O_2, CH_4, and CO_2, which are indicator compounds of aerobic and anaerobic conditions (Figure 7-41). In general, the depth of the anaerobic vadose zone closely corresponds to the depth of contaminated soil. Concentrations of aerobically degradable compounds are relatively low in the aerobic zone (where O_2 is present) but can be quite high in the underlying anaerobic zone. The thickness of the zone in which conditions change from anaerobic to aerobic conditions is typically less than 2 feet (Davis, Patterson, and Trefry 2009).

Ideally, the deepest soil vapor sample point is located near the top of the contaminated soil or near the contaminated groundwater. The depth to the top of the contamination might be known from preexisting site assessment data,

but it is advisable to confirm this depth in the field before installing vapor sample points. This confirmation is easily done by screening the soil vapor with a portable PID or FID or by screening the soil vapor for O_2 using a portable meter. Additional soil vapor sample points are then installed from the top of the contaminated zone upward in the vadose zone. Typically, three or four sampling depths are all that are necessary to locate and document the biodegradation zone. Procedures for constructing soil vapor sampling points are discussed in the following sections.

7.5.4.7. Sub-Slab Vapor

Sub-slab samples refer to active or passive vapor samples collected from immediately below a slab-on-grade or a basement floor slab. Sampling methodologies are presented in **Sections 7.3** and **7.4** of this chapter. Indoor air and sub-slab vapor sampling are sometimes performed sequentially, in order to evaluate the potential for VI and/or establish building-specific AFs. When sampling both media, it is good practice to collect indoor air first.

Special considerations for sub-slab vapor sample include the following:

- Sub-slab samples should be avoided in areas where groundwater might intersect the slab.
- Underground utilities (for instance, electric, gas, water, tension rods, or sewer lines) should be located and avoided.
- If a vapor barrier already exists under the slab, sub-slab sampling might puncture the barrier. Therefore, if a sub-slab probe is installed, careful resealing will be required after monitoring is complete.
- For basements, primary entry points for vapors might be through the sidewalls rather than from below the floor slab. As such, sub-slab samples might need to be augmented with samples through the basement walls.
- Sample collection and analysis is analogous to other types of soil vapor sampling, as described below; however, risk-based screening levels for sub-slab samples may be lower than those for deeper soil vapor samples, requiring an analytical method with lower detection limits.
- Recent studies have confirmed that temporal variations in sub-slab vapor concentrations can be less than a factor of two and occur over longer time scales (weeks), so short duration samples (5 to 30 minutes) are representative (Lutes et al. 2021; Zimmerman et al. 2024).
- There can be large spatial variability in sub-slab vapor samples by factors of 100 or more (Folkes et al. 2009; Luo et al. 2009).

As presented in **Section 7.3.1**, the number and location of sub-slab vapor sampling points used in the assessment of the VI pathway should be determined based on a review of the site history, the building type (e.g., residential, commercial, or industrial), the location of footers (which could create isolated zones of soil vapor), and potential VI risk posed to inhabitants. Many states provide specific guidance on the number of points required based on the square footage of the slab. These state-specific requirements can range from one sample for every 500, 1,500, or 5,000 square feet to 22+ for a building over 100,000 square feet. In general, two points are required if the slab is less than 1,500 square feet, with additional points added as the square footage increases (e.g., Tennessee DEC 2023).

If source areas are not known, the points should generally be equally spaced within the slab being assessed. If the source area is known, then points should target potential hot spots. Care should be taken to avoid placing the points within 5 feet of an exterior wall or large crack as these can be influenced by atmospheric air (USEPA 2012a). In addition, it is important to understand key questions requiring answers prior to selecting sample locations. These can be related to risk screening levels relative to predicted

indoor concentrations, empirical AF determination, the need to generate a rendering of the spatial distribution of subsurface concentration distributions, and the need to measure differential pressure; they can also be related to mitigation design and performance monitoring.

7.6. Other Media Sampling Methods

In addition to the media mentioned in Sections 7.4 and 7.5, some VI investigations include the sampling of other media, including groundwater, soil, and NAPL as well as other vapor transport pathways such as utility conduits. This section discusses methodologies for the sampling and analysis of these media, specifically in relation to VI investigations.

7.6.1. Groundwater

For sites with groundwater impacts, practitioners typically conduct groundwater sampling throughout the life cycle of the project. This can include the collection of initial samples (e.g., grab groundwater samples), samples to monitor remedial progress (e.g., routine sampling to monitor natural attenuation), or post-remedy samples (e.g., confirmation sampling). Groundwater sampling can also be an important component of assessing VI at a site, particularly when groundwater is shallow and impacted with VFCs. The following sections present some basic information on collecting groundwater samples to support a VI project. For more details regarding groundwater sampling, refer to the USEPA guidance (USEPA 2023).

Table 7-5. Groundwater sampling methods for vapor intrusion investigations.

Methods	Example Guidance Documents	Advantages or Disadvantages
Passive Samplers	• NJDEP *Field Sampling Procedures Manual* (NJDEP 2024) • United States Geologic Survey *User's guide for polyethylene-based passive diffusion bags to obtain volatile organic compound concentrations in wells, Part 1* (Vroblesky 2001) • ITRC *Technical and Regulatory Guidance for Using PDBs to Monitor VOC in Groundwater* (ITRC 2004) • ITRC *Passive Sampling Technology Guidance* (ITRC 2024)	• Can use existing wells for ongoing monitoring • May not be adequate where: o VFCs are highly soluble in water (such as methyl tertiary-butyl ether [MTBE]); dual-wall PDBs may eliminate this problem; speak to the manufacturer o in-well vertical flow occurs o permeability is very low
Low-Flow Purging and Sampling	• NJDEP *Field Sampling Procedures Manual* (NJDEP 2024), Sections 7.9.2.2 and 7.9.2.3	• May generally target interval closer to the water table in some settings • Discrete interval sample not assured
Volume-Averaged Purge and Sample Collection	• NJDEP *Field Sampling Procedures Manual* (NJDEP 2024), Section 7.9.2.4	• Not recommended to generate new groundwater data specifically for VI investigations because of the potential for vertical averaging

Note: PDB = passive diffusion bag

Table 7-5, prepared by NJDEP (2024), summarizes some alternative groundwater sampling methods that may apply to VI investigations. Sampling guidance for VI investigations may differ from other guidance in the documents because of the objective to determine very shallow groundwater quality.

7.6.1.1. Active Groundwater Sampling

If evaluating the VI pathway is the only sampling objective, use two modifications to the typical low-flow purging and sampling:

- Set the pump intake level as close to the water table as possible without significant risk that the water level will drop and expose the pump intake. For wells in formations with average or high permeability, about 1.5 to 2 feet below the static water level should be an adequate intake location.
- The purging objective is to flush two to three volumes of groundwater through the sampling array (such as tubing and pump). While measuring water quality indicator parameters is preferred (but not necessary), drawdown should be measured and ideally not exceed 0.3 feet (USEPA 2002a).

7.6.1.2. Passive Groundwater Sampling

Passive samplers are available in several varieties, as described in the ITRC documents listed in the table above. Passive diffusion bags (PDBs) currently may be the most common tool for sampling VFCs. PDBs should be deployed just below the water level in a well for a minimum of two weeks to equilibrate with the well water. Significant water-table fluctuations during that period will affect the appropriate depth intervals for the samplers. If the water level drops below the sampler, then transfer of volatiles from the sampler water into less contaminated well air space occurs; the sampler should be resuspended two feet below the current water level and retrieved after an additional two-week equilibration period. In any event, the depth to water in the well should be measured when the PDBs are installed and removed, and the position of the samplers relative to the water level should be clearly described in the report presenting the PDB data. Single-wall PDBs are not applicable to all compounds (for example, SVOCs and soluble compounds such as acetone, styrene, MTBE, and 4-methyl-2-pentanone), so the target analytes must be confirmed. Other passive samplers (e.g., dual-wall PDBs) may be used for detecting and reporting these compounds but confirm this with the manufacturer. More information is available in the ITRC *Passive Sampling Technology Guidance* (ITRC 2024).

7.6.2. Soil

7.6.2.1. Analytical Soil Data for Evaluating Vapor Intrusion

As a result of the uncertainty associated with using partitioning equations and the potential loss of VFCs during sample collection, analytical data for soil are not typically used for evaluating VI risk. The VI pathway can be evaluated with soil data when soil vapor sampling is not feasible at a site because of low-permeability or saturated conditions or when only soil data are available, especially for sites impacted with aerobically degradable compounds. Existing soil data could be used as part of an MLE approach.

To perform VI risk calculations using soil data, contaminant concentrations in soil must be converted to soil vapor concentrations using assumptions about the partitioning of the contaminant into the gas phase. Soil solid–to–soil vapor partitioning equations are readily available but using them increases the uncertainty in evaluating VI. Calculated soil vapor values for aerobically degradable compounds from soil data often overestimate actual soil vapor concentrations (Golder Associates Ltd. 2007). Conversely, soil data for chlorinated hydrocarbons often underestimates soil vapor concentrations.

Obtaining soil data for a site's VFCs, however, can play an important part in establishing the CSM, which in turn guides the decision-making process for a VI investigation. Under the right circumstances (e.g., finer soils or presence of NAPL), establishing the extent of impacts in soil can lead to source delineation, which can then guide decision-making for further investigations, particularly when it comes to sampling locations for soil vapor, sub-slab vapor, indoor air, etc. Additionally, identifying important physical

characteristics of the soil at a site can be vital in assessing the feasibility of a mitigation and/or remediation strategy.

7.6.2.2. Physical Properties of Soil

Site-specific soil properties such as bulk density, grain density, total porosity, moisture content, and fraction of organic carbon can be measured from soil samples and the results used to replace default input parameters when models are used. Air permeability of the vadose zone can be determined from either in situ measurements or laboratory measurements. In situ measurements test a larger portion of the subsurface than a laboratory measurement of a small core sample and are the preferred method. In situ measurements of air permeability can be conducted in the shallow vadose zone or in the area of the vadose zone subject to advection by building-driven depressurization or conducted to assess the presence of low-permeability layers in the vadose zone, which may act as partial vapor barriers.

7.6.2.3. Screening

Field-screening tools can be a great first step when assessing impacts of VFCs in soil. For sites with chlorinated solvents and/or aerobically degradable compounds, the following tools can be very helpful for screening purposes.

7.6.2.4. Membrane Interface Probe

A membrane interface probe (MIP) is used to screen soil (and sometimes groundwater) for VFCs. The MIP tooling (**Figure 7-42**) is advanced vertically to a targeted depth using direct push drilling methods, such as a cone penetrometer testing (CPT) rig. From each target interval, the MIP collects measurements of VFCs by capturing a vapor sample through a permeable membrane, which is then transported using a carrier gas to the detector at the surface. The MIP tooling is commonly equipped with a PID, FID, ECD, and/or DELCD, which can be used to identify the presence of VFCs in soil vapor, dissolved phase, and LNAPL or DNAPL in soil. When used in tandem with CPT, lithology and hydrogeology can also be evaluated. As the measurements collected using the MIP are semiquantitative, results are considered relative and subject to confirmation via laboratory analysis.

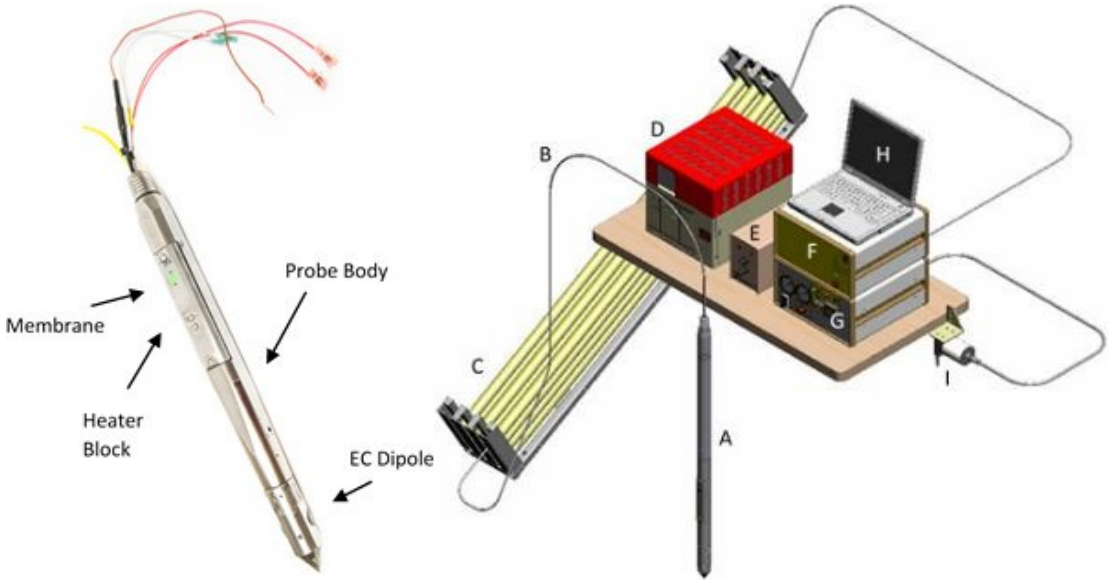


Figure 7-42. Membrane interface probe tooling (left) and the receiver (right).

Source: ITRC (2019).

7.6.2.5. Headspace and Other Field Monitors

Some agencies are considering allowing soil headspace concentrations to be used as criteria for defining a sufficient thickness of non-source (clean) soil for screening out sites for VI investigations. Factors to consider in order to obtain consistent headspace readings include the following:

- The use of a consistent methodology
- The effect of container materials on sample integrity
- Awareness of variations in PID response at high humidity
- The effect of soil type on VFC concentrations in the headspace

Several state agencies have established their own methodology; see, for instance, Massachusetts's guidance (MassDEP and ABB Environmental Services, Inc. 1994). This method uses the original jar method rather than plastic baggies.

Headspace concentrations are affected by the size of the container, amount of sample, the size of the available headspace, temperature, development time, hold time, and analysis time. In addition, the permeability of the container and any contamination from the container should also be considered. There is evidence that some baggies are not impervious to aerobically degradable compound vapor migration, which could lead to artificially low results—reported to be as much as a factor of two.

The issue of variable PID response at high humidity was documented in a study reported by the Maine Department for Environmental Protection (MEDEP 2009). This study discussed the applicability of soil headspace in various scenarios and reported variations in PID response by brand. Aerobically degradable compound response over a wide range of humidity varied from unit to unit by up to a factor of four. Note that calibration using 100 ppm isobutylene does not correct for humidity because it is a dry gas mixture and therefore fails to compensate for moisture that is always present in soil samples used for headspace analysis.

In addition to measuring headspace, other field parameters that may assist in assessing VI include oxygen, CO_2, hydrogen sulfide (H_2S), and methane, all of which can be measured using field monitors. Based on your project's DQOs, additional field monitors to consider include multi-gas meters, FIDs, and landfill gas monitors (e.g., the GEM-2000).

7.6.2.6. Shake Test

A shake test is a field method by which soil and deionized water is placed in a small jar that is sealed and shaken, then allowed to settle (Figure 7-43). This can provide a better understanding of a soil's grain-size distribution and indicate whether LNAPL is present. As mentioned in Section 9.2, grain-size distribution can be important parameters for modeling and/or assessing the potential for vapors to migrate through the soil. Identifying the presence, or lack thereof, of

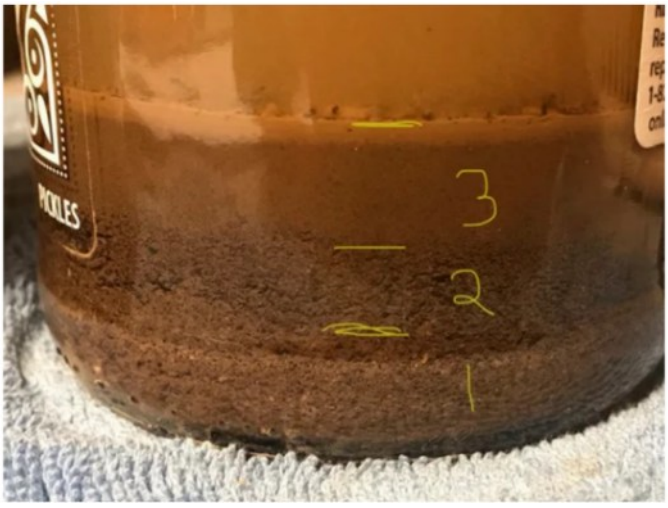


Figure 7-43. Grain-size distribution as shown after settlement during a shake test.

Source: California Department of Toxic Substances Control, used with permission.

LNAPL can be important in determining the source zone of a vapor plume. It is important to note that the information derived from a shake test will not replace the need for laboratory data.

7.6.2.7. Collecting Soil Samples for Laboratory Analysis

7.6.2.7.1. Drilling Methods

When a project's DQOs include the collection of soil samples for the analysis of VFCs and/or aerobically degradable compounds, the chosen drilling method is very important. Methods that least disturb the soil, such as direct push, are preferred. If using a hollow-stem auger, be sure that the soil samples themselves are collected using a core barrel fixed with a split-spoon sampler. Similarly, if using a hand auger, be sure to use a slide hammer when collecting the actual soil samples.

More importantly, there are several drilling methods that one should avoid using. Reverse air and reverse mud use either air or a drilling solution to pull the soil cuttings up to the surface. VFCs will have likely been completely volatilized, and this will make collecting a sample for laboratory analysis pointless. Similarly, the soil cuttings obtained during sonic drilling will be disturbed and, depending on soil composition, may be subjected to drilling-induced heat, resulting in the volatilization of VFCs (ASTM International 2024). Sonic drilling can be very good for logging soil lithology.

7.6.2.7.2. Collection Methods

Field extraction with methanol or hexane can be good for reducing volatilization losses. When sampling soil for VOCs and/or TPH in the gasoline rage (TPH-g), soil samples should be collected using procedures specifically designed to minimize volatilization losses, such as SW-846 Method 5035A (USEPA 2002b) and augmented USEPA Method 5035A (California DTSC 2004). More details on the interpretation of soil data and phase partitioning calculations can be found in the CalEPA DTSC *Vapor Intrusion Guidance* (California DTSC 2011). Existing soil data should be used as part of the MLE approach. It is important to note that while this method can reduce volatilization losses, it can result in elevated detection limits.

7.6.2.7.3. Passive Soil Collection

Collecting a soil sample using a thin-walled sampler (e.g., shelby tube) is considered a passive soil sampling method. These samplers are often used to collect undisturbed soil samples to assess geophysical properties but have also been used to assess NAPL in soil. Like the shake test, these data can be important in determining a source zone and/or the feasibility of a proposed remedial and/or mitigatory action.

7.6.3. Nonaqueous-Phase Liquid

Nonaqueous-phase liquid (NAPL) refers to organic liquids that are immiscible (not soluble) in water. There are two types of NAPL: LNAPL are less dense than water, and DNAPL are denser than water. The presence of NAPL at a site typically provides additional complications for evaluating VI. For example, concentrations of chemicals in soil vapor can be excessively high, which can cause field and laboratory instruments to malfunction and/or go out of calibration. Additionally, remediation of impacted soil vapor realistically cannot begin until the NAPL is addressed because it will continue to provide a source of elevated concentrations.

Several methods can be used to verify the presence of NAPL at a site. Some of these are presented below.

7.6.3.1. Light Nonaqueous-Phase Liquid

Petroleum is the most common example of LNAPL encountered at sites with potential VI concerns. While petroleum is often readily identifiable in a monitoring well as a separate phase (mobile LNAPL), it may also be present as a residual phase, trapped in pore spaces or fractures in soil and bedrock (residual LNAPL). When LNAPL is present at a site, BTEX and other volatile compounds will typically be in soil vapor at elevated concentrations.

Mobile LNAPL is easily identifiable. In groundwater, LNAPL will partition to the top. In soil, it should be clearly visible as a nonaqueous substance with a sheen and/or strong petroleum odor. When collected in a bailer or sampling vessel, the two separate liquids should be clearly visible (Figure 7-44). There are several field tests (dyes, shake tests, fossil fuel traps, and UV lightboxes) that can be used as MLE for the presence, or lack thereof, of residual LNAPL (ITRC 2018). Undisturbed soil cores can also be collected for submittal to a laboratory that specializes in UV photography. When using this procedure, the cores must be frozen immediately after collection and remain frozen during shipment to the laboratory. Additionally, practitioners can use high-resolution screening tools, such as laser-induced fluorescence (LIF), to identify and delineate LNAPL in the subsurface. LIF describes a field-screening process by which fluorescent molecules (referred to as *fluorophores*) in petroleum-based oils and lubricants and naturally occurring organic materials can be detected. LIF can help locate NAPL source areas and can assist with monitoring network design. For additional details regarding methodologies for screening, quantifying, and delineating LNAPL at a site, refer to ITRC (2018).



Figure 7-44. Visible light nonaqueous-phase liquid in soil after a shake test where red dye powder and water were added.

Source: California Department of Toxic Substances Control, used with permission.

Should one of these tests identify the presence of LNAPL, VI investigations should be adjusted to account for vapor-phase samples with excessively high concentrations of petroleum products and/or BTEX.

7.6.3.2. Dense Nonaqueous-Phase Liquid

DNAPLs consist of chlorinated and nonchlorinated nonaqueous-phase hydrocarbon compounds that are denser than water. Unlike LNAPLs, DNAPL compounds released in significant quantities at the surface can migrate to depths below the capillary fringe and water table due to their relatively high density. Once below the water table, these contaminants can exist as an undissolved separate DNAPL and/or partition into the aqueous phase, generating a dissolved plume. Although DNAPL compounds are insoluble enough to remain nonaqueous, they are soluble enough to yield concentrations exceeding regulatory thresholds over extensive volumes and distances from the release. Due to low interfacial tension between chlorinated DNAPL chemicals and groundwater, soils generally have low retention capacity for these compounds, thereby facilitating deep penetration into the subsurface and subsequently large water-NAPL contact areas. For deep-penetrating DNAPLs, local and regional groundwater flow can lead to extensive aquifer degradation over large vertical ranges (several hundred meters) and lateral distances (several kilometers). In addition, DNAPL source zones can result in potential long-term VI exposures via partitioning from the source as well as from the dissolved phase into the vapor phase.

Screening for DNAPL at a site is difficult because there are very few tools designed to identify it. Unlike LNAPL, there are no simple field tests practitioners can use to identify DNAPL below groundwater. It is very challenging to locate DNAPL due to its complex spatial configuration and inability to be located using water solubility alone. Research has shown that DNAPL is often found in areas where the aqueous concentrations of the specific compounds are well below the 1% threshold often used to identify DNAPL (ESTCP 2011). While often incorrectly depicted as pools, DNAPLs can reside in a relatively small portion of the soil column as threadlike ganglia and globules. Some high-resolution screening tools, such as LIF and MIP, can assist in identifying these source zones. Direct contact with source-zone globules is typically required for detection. While LIF systems are not presently capable of directly detecting pure DNAPLs, many of the hydrocarbon compounds they can detect are miscible with DNAPLs and can become commingled with these materials (Kram 1998; 2002; 2006). More recently, LIF sensor probe systems equipped with dye introduction capabilities have been commercialized (Einarson et al. 2018). For these systems, a fluorescent dye that is miscible with chlorinated solvent DNAPL is injected into the subsurface as the probe is advanced to help locate. See Section 3.4 of ITRC's *Advanced Site Characterization Tools* guidance for more information on LIF methodologies. The MIP, which is described in **Section 7.6.2.4** of this document, can also be used to identify DNAPL source zones by locating solute concentrations approaching the solubility limit of the target analytes.

7.6.4. Sewer and Other Utility Conduits

Chapter 4: Conceptual Site Model and the **Vapor Intrusion Preferential Pathways Fact Sheet** present an explanation of preferential pathways, including updated nomenclature and their effects on VI. A conceptual model for VI from groundwater through utility conduits such as sewer lines is further explained by Beckley and McHugh (2020). Collecting and analyzing samples from these features may be an integral part of a VI evaluation. The focus of this subsection is on the methodologies used to collect samples from these pathways. Note that many of the following subsections will link to previously described methodologies. Additionally, practitioners should confirm applicability and sampling guidance with their local regulatory agency.

7.6.4.1. Utility Conduits

The headspace within utility conduits can be sampled using the same/similar procedures as used for collecting active and/or passive crawl-space samples (presented in **Sections 7.3.2**, **7.4.1**, and **7.4.2**). Sampling approaches include screening, active, and passive options. Some of these include on-site measurements, while others require fixed laboratory analyses) Sewer lines and connected drainages are the most commonly sampled utility conduit. Sewer lines are best accessed through cleanouts located within or near the building or a sewer manhole in the street. Note that sewers are not typically accessed from a building's interior due to the presence of a p-trap, which is explained in further detail in **Section 7.6.4.3**. Practitioners should coordinate with their suppliers and/or laboratories as some have sampling equipment specifically designed for sampling sewers. Many states have not provided guidance on sewer sampling; however, some, such as Indiana and Wisconsin, do have sewer sampling protocols included in their guidance documents (IDEM 2022; WDNR 2018). Sewer investigative protocols are also detailed in the ESTCP Report *Sewers and Utility Tunnels as Preferential Pathways for Volatile Organic Compound Migration into Buildings: Risk Factors and Investigation Protocol* (McHugh and Beckley 2018). A depiction of sewer gas sampling is shown in **Figure 7-45**. Interpretation of data from utility sampling is included in the **Vapor Intrusion Preferential Pathways Fact Sheet**. It should be noted that syringe samples can be collected from sewers and sewer cleanouts and analyzed in the field using a real-time chemical-specific analyzer; however, these should be considered grab samples and only used for screening purposes.

Other utility conduits include electrical conduits and storm drains. Many of these conduits can be accessed from the inside of buildings or ports located near an exterior wall. If it has been determined that an electrical conduit may be a potential pathway, be sure to turn off power prior to sampling. Note that

gas lines are not typically sampled when evaluating VI due to potential VFCs that are in natural gas and because these lines are under pressure.

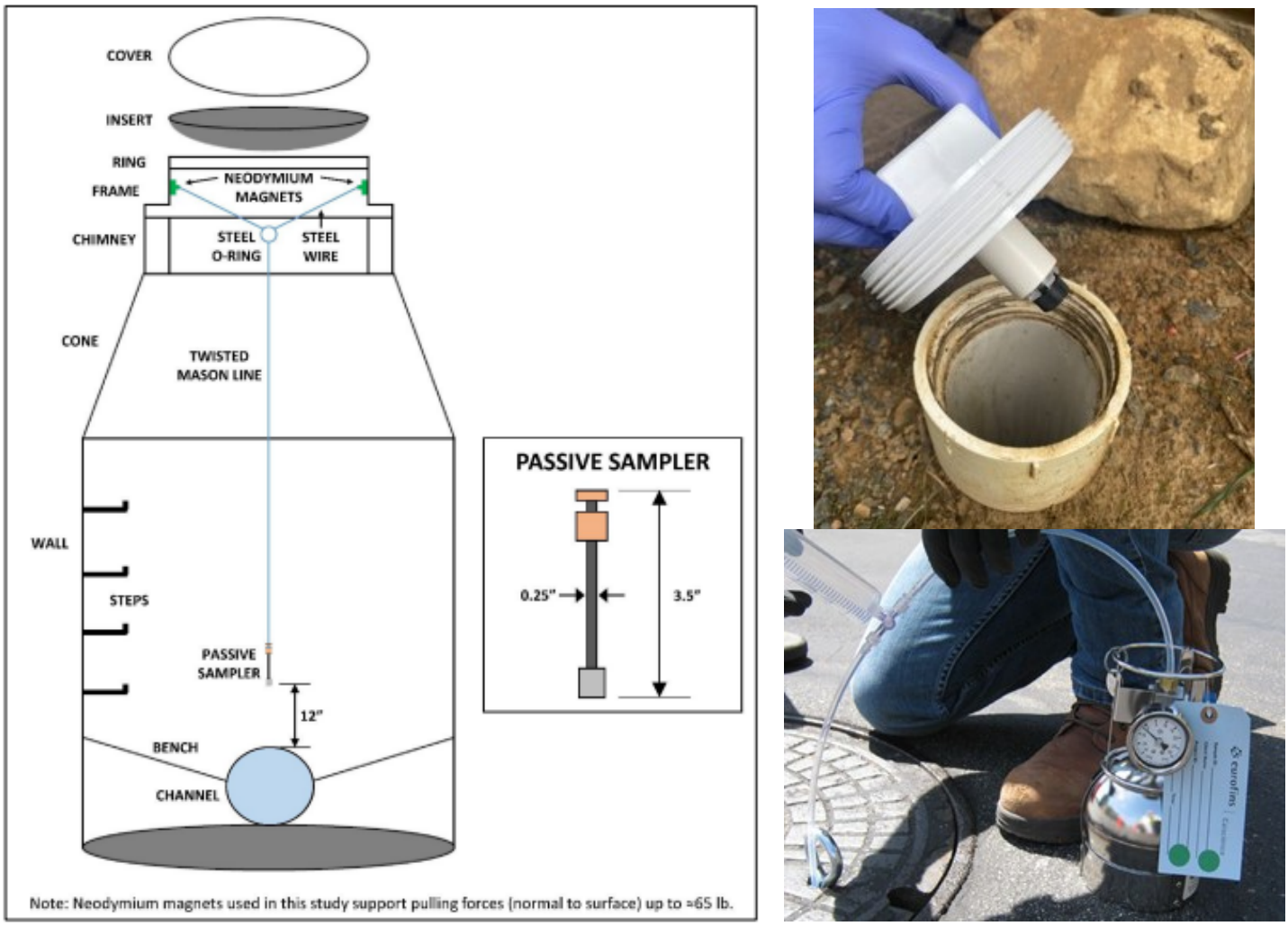


Figure 7-45. Diagram (left) of typical setup for collecting a passive sewer gas sample, photograph showing the collection of a passive sewer gas sample (top right), and a photograph showing the collection of an active sewer gas sample (bottom right).

Source: Jame Evan Willet, 2018 (left and top right); California Department of Toxic Substances Control (bottom right), used with permission.

7.6.4.2. Utility Backfill

Although backfill material in utility corridors may be more permeable than the adjacent native soil, backfill does not necessarily provide a preferential pathway for vapor transport (see the **Vapor Intrusion Preferential Pathways Fact Sheet** for more information on VIPPs). As noted by McHugh and Beckley in 2018, VFC "concentrations can be relatively high in soil gas collected in backfill (e.g., near source areas). However, it is unlikely that appreciable lateral migration would occur unless the backfill was isolated within an impermeable matrix and a pressure gradient or strong driving force was present within the backfill. Further, at diffusion dominated sites, transport will not occur preferentially through higher permeability backfill"(McHugh and Beckley 2018, 26).

If the site-specific CSM warrants sampling soil vapor in backfill, the collection of vapor samples is essentially the same process used in the collection of active or passive soil vapor samples as discussed in Sections 7.3 and 7.4. The location of the utility should be carefully mapped, in concert with the utility owner, to understand not only the lateral extent of the utility, but also its depth. Locating the proper placement of the sampling points is perhaps the most difficult aspect of this sampling method. It may be beneficial to work from beyond the limits of the utility toward the utility itself until you enter the backfill material.

7.6.4.3. P-Trap Sampling



Figure 7-46. P-trap sampling.

Source: Geosyntec Consultants, used with permission.

Plumbing traps (p-traps) are generally u-shaped portions of drain systems that contain wastewater from sinks, toilets, and floor drains, as shown in Figure 7-46. The water within the trap prevents the intrusion of sewer gas into the building envelope. The procedure for sampling p-traps is very similar to the crawl-space sampling procedures presented in Sections 7.3.2, 7.4.1, and 7.4.2. While the water in the p-trap stops the sewer gas from entering the building, it can still enter through cracks or plumbing fitting elsewhere, so a sample of the sewer gas should be collected. Collecting a sample of sewer gas beyond the p-trap can be accomplished by inserting small-diameter tubing into the p-trap, through the wastewater, and into the void space of the drain line that leads out of the building. See the Soil Vapor Probe Installation Toolbox Fact Sheet for a discussion of suitable tubing materials. This method is limited to the collection of active sewer gas samples. Prior to sampling, the line should be evacuated either by forcing air through the tubing, or by purging the tubing to remove water that may have entered the tubing. It should be noted that improper (or do-it-yourself) plumbing can itself be a source of sewer gas intrusion into a building. As this could impact indoor air sampling results, practitioners should be sure to check that p-traps are installed properly before sampling.



Figure 7-47. Vent stack sampling.

Source: California Department of Toxic Substances Control, used with permission.

7.6.4.4. Plumbing Vent Stack

Plumbing vent stacks are designed to keep the pressure within a plumbing system equal to atmospheric pressure. The vent stack allows wastewater to drain from the system without causing a siphoning effect that would evacuate wastewater from p-traps and avoid a buildup of pressure from the sewer that could force sewer gas into the building envelope.

Like sewer cleanout and manhole samples, vent stack samples can be used to obtain a general understanding of the chemicals that are contained within sewer gas. The procedure for collecting active and passive vent stack samples is very similar to the crawl-space sampling

procedures presented in Sections 7.3.2, 7.4.1, and 7.4.2. When collecting active sewer gas samples from these features, a small-diameter valved fitting can be installed within the vent stack, and the tubing can be affixed onto that small-diameter valve (Figure 7-47). Passive samples can be collected by lowering the sampling device into the vent stack from the roof. Like other utilities, it should be noted that syringe samples can be collected from vent stacks and analyzed in the field using a real-time chemical-specific analyzer; however, these should be considered grab samples and only used for screening purposes.

7.7. Supplemental Tools and Methodologies for Physical Vapor Intrusion Characteristics

Beyond obtaining concentration data in various media, collection of screening-level data and physical attributes and characteristics can help better understand processes controlling VI. For instance, advective transport of vapors through a building foundation can be documented by measuring the differential pressure between the subsurface and indoor environments. This can tell field personnel whether vapors are intruding during sampling campaigns, which would be reflected in a situation where the subsurface pressure is higher than the indoor pressure. In addition to pressure monitoring, tracers can be used to support evaluation of transport characteristics, to evaluate mitigation system performance, and to estimate building-specific AFs. This section describes a few select applications where collection of physical measurements along with concentration data provides insight into the assessment of VI.

7.7.1. Additional Uses for High-Volume Sampling

The methodology for performing HVS is presented in the High-Volume Sampling Fact Sheet. Beyond providing a spatial average of sub-slab vapor concentration at large buildings, HVS can be utilized to assess multiple physical characteristics in support of a VI investigation. The data collected during HVS can be used to support the CSM and/or obtain design parameters for a potential mitigation system. Uses include source delineation, static vacuum field testing, helium trace testing, and transient vacuum field testing.

7.7.2. Differential Pressure Monitoring and Building Pressure Control

Differential pressure can be checked in the field to provide MLE to evaluate VI by using a digital micromanometer attached to a sub-slab soil vapor probe. It is often advisable to use one with data-logging capabilities and assess the response to wind speed and barometric pressure changes if these data are collected. Some models can also deliver this data directly to the internet for near-real-time monitoring and for combining with other data types (Kram et al. 2020).

Another possible method for distinguishing subsurface VI from background sources is BPC. Indoor air samples are collected with and without manipulating the pressure differential from the subsurface to indoor air. This can be accomplished by pressurizing the building or depressurizing the region beneath the floor slab. In both cases, if the applied pressure differential is sufficient to prevent subsurface VI, the concentrations of chemicals intruding from the subsurface will be reduced and the concentrations of chemicals from background sources will be largely unaffected.

Specifics on differential pressure monitoring and BPC are presented in the Pressure Monitoring and Building Pressure Control Fact Sheet.

7.7.3. Flux Chamber and Other Flux Measurement Devices

Flux chambers are enclosures placed in sealed contact with the surface (e.g., ground, floor) for a period of time, and the contaminant concentration in the enclosure is measured (Figure 7-48). In theory, an

effective room concentration can be calculated from the measured flux by assuming the flux is constant over time and over the floor area of the room, and assuming a room ventilation rate (RVR). The calculated room concentration can be compared directly to allowable room concentrations for the volatiles of interest. This method offers advantages in some cases because it yields the actual flux of the contaminant out of the ground, which eliminates some of the assumptions required when using other types of subsurface data. This method has long been used by regulatory agencies at hazardous waste sites, and it is widely used for measuring trace emissions from natural soils, but its application to VI assessments is relatively limited.

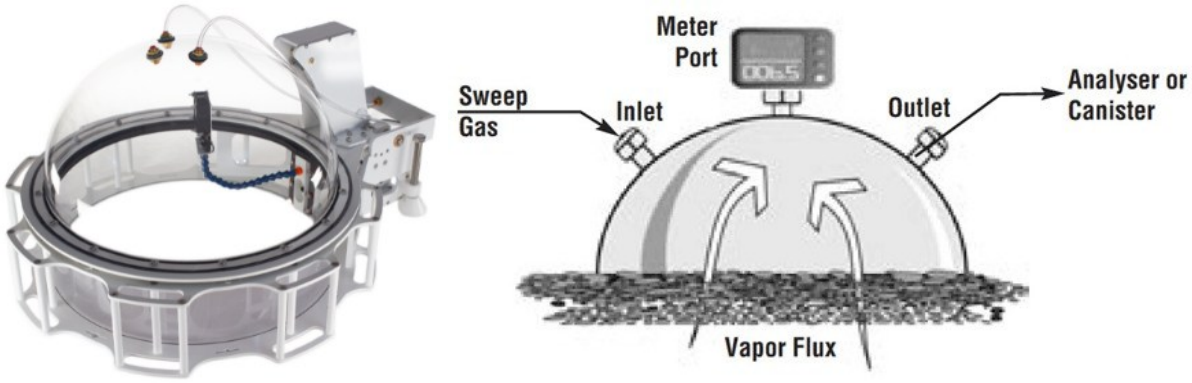


Figure 7-48. Photograph (left) and diagram (right) of a typical mass-flux chamber.

Source: Eosense.io (left); Hawai'i State Department of Health's Hazard Evaluation and Emergency Response Office (right), used with permission.

Flux testing is typically conducted in one of two modes: dynamic or static. In dynamic systems, a sweep gas is introduced into the chamber to maintain a large concentration gradient across the emitting surface. The effluent air from the chamber is collected using canisters and analyzed for VFCs. This method is best suited for situations where large fluxes are anticipated. In static systems, a chamber is emplaced, and the contaminant concentration buildup is measured over time. This method is best suited for situations where lower fluxes are anticipated. Additional details on the methodologies for flux chamber sampling are presented in the **Flux Chamber and Other Flux Measurement Devices Fact Sheet**.

7.7.4. Using Tracers for the Determination of Slab-Specific Attenuation Factors and Room Ventilation Rates

Using tracers in VI assessments offers several key benefits for determining the slab-specific attenuation factor (SSAF) and RVRs. Tracers provide accurate, real-time measurements of how VFCs move through building slabs and are attenuated before entering indoor spaces, enabling precise calculations of SSAF. They also help assess the ventilation efficiency of a room by determining the RVR, which is crucial for understanding how quickly VFCs are diluted or removed from the indoor air. This method is noninvasive, cost-effective, and efficient, reducing the need for disruptive sampling and providing rapid insights into vapor behavior under varying conditions. Overall, tracers enhance the accuracy of risk assessments, guide remediation strategies, and ensure compliance with health and safety standards while offering flexibility across different building types and environments. For more details on the use of tracers in VI investigations, refer to the **Tracers for Determination of Attenuation Factors and Ventilation Rates Fact Sheet**.

7.7.5. Vapor-Forming Chemical Source Determination

Some approaches attempt to determine the source of detected volatiles through a detailed study of the nature of contamination with a focus on MLE to potential sources (see the **Multiple Lines of Evidence Fact Sheet**). Traditional ESAs focus on the nature and extent of contamination as determined by common methodologies developed to provide data for regulatory purposes. The environmental forensics approaches are more sophisticated analytical techniques that can produce chemical fingerprints that are source specific. Potential fingerprinting strategies include the use of compound ratios, distinguishing between different hydrocarbons, and the use of isotope ratios. For more information, refer to the **Approaches for Vapor-Forming Chemical Source Determination Fact Sheet**.

7.8. Advantages and Disadvantages of Various Investigation Strategies

7.8.1. Relative Advantages of Investigation Methods

Table 7-6 below details the advantages and disadvantages of the various VI investigative methodologies.

7.8.2. Common Vapor Intrusion Investigation Limitations

Variability in contaminant concentrations at a VI site can have important implications for site management. That variability needs to be considered when evaluating measured concentrations against applicable standards. Considerable progress has been made in quantifying typical variations, and some important generalities can help understand that variation. Those generalities may allow a limited set of concentration measurements to be used to show that the concentrations measured at a site are expected to be below applicable standards, despite expected variation. Even if the concentrations still indicate a concern, the variation may be the result of a process that should become an important part of the CSM and will inform decisions about site management. Various techniques have been developed to better understand these variations, such as real -time monitoring (**Section 7.2.2**) high-density indoor air sampling, HVS (**Section 7.4.5**), and BPC (**Section 7.7.3**). Those techniques can produce valuable, site-specific data about observed variations.

7.8.2.1. Spatial Variability

Variations in soil vapor concentrations due to spatial variability are principally due to underlying lithology, chemical type, multiple potential source areas, movement of VFCs along various preferential pathways, and potential influences from any overlying building (e.g., continuing sources, HVAC systems, or pressurized building envelopes. Variations will depend on which of these characteristics are at play. For example, lithology could result in a variation of concentrations based on the locations of fine versus coarse-grained intervals. At a site with a relatively uniform lithology, variation could be a result of target VOCs in the presence of other VFCs. These variations can be problematic because they can produce acceptable contaminant concentrations during one event and unacceptable concentrations during the next event. Toward that end, it is important to understand the source and scale of these variations. For assessing the extent of soil vapor migration from the subsurface vapor source, USEPA generally recommends measuring soil vapor concentrations from either sub-slab vapor or soil vapor probes, with a sufficient density to characterize and understand spatial variability (USEPA 2015a).

Table 7-6. Advantages and disadvantages of the various vapor intrusion investigative methodologies.

Measurement	Relative Advantages	Relative Disadvantages	Comments
Deep Soil Vapor (>5 feet below slab)	• Existing data may already be available for some sites. • Less chance of short-circuiting by atmospheric air. • Temporal variations in concentration minimal.	• Data may not be representative of soil vapor concentrations at shallower depths due to intervening soil layers. • Does not account for aerobic biodegradation in shallower soil layers.	When combined with other data, deep soil vapor data can provide evidence of attenuation as a function of vertical transport distance; however, deep soil vapor sampling is conservative for screening purposes.
Shallow Soil Vapor (<5 feet below slab or basement floor)	• Standard equipment and approaches have been developed. • Media most likely to intrude into receptors. • Data can be collected outside the building.	• Rate of vapor transport to the building must be estimated. • May not reflect sub-slab concentrations. • Greater temporal variability than deeper soil vapor data.	Building zone of influence must be taken into consideration in sampling design. Shallow soil vapor sampling may not be conservative for screening purposes.
Sub-Slab Soil Vapor	• Provides more representative subsurface data for sites with surface releases (e.g., spills and leaks). • Gives concentrations immediately below building and receptors.	• May contain contaminants from interior sources. • Highly intrusive; requires building access and drilling through slab/floor. • Rate of vapor transport into the building must be estimated. • Conservative screening levels.	Preferred approach of many regulatory agencies. Concurrent determination of slab-specific attenuation factor may be useful to interpret data.
Emission Flux	• Measures actual contaminant emissions from subsurface. • Considers all subsurface processes such as biodegradation, advection, and sorption. • Eliminates interpretation using attenuation factor or model.	• Equipment and experienced staff may be difficult to find. • Selection of representative sampling locations may be difficult. • Biased low results if emission hot spots are not sampled. • Not considered by most regulatory agencies.	This approach is best suited for evaluating future-use scenarios on undeveloped land, houses with dirt floor basements or crawl spaces, and to confirm bioattenuation in shallow vadose zone (<3 feet bgs).

Measurement	Relative Advantages	Relative Disadvantages	Comments
Subsurface Tracer	• Naturally occurring compounds (e.g., radon-222) can be used in some cases. • Provides a direct measure of attenuation across a slab. • Typical values often >10 times lower than default values.	• Usually requires separate analytical method than those used for target compounds. • If radon is used, investigator may find indoor concentrations exceeding health-risk levels. • Radon not present everywhere at levels distinguishable from background.	Method assumes that the tracer and subsurface contaminants move into the building at the same rate.
Indoor Air	• Direct measurement of contaminant concentrations in buildings. • May be more convincing to occupants.	• Background sources complicate data interpretation. • Requires access to indoor space. • For residential sites, a building survey prior to sampling is often necessary. • Very low reporting limits may be required for some compounds (e.g., TCE). • One-time sampling results may not be representative of long-term average concentrations. • Poor sample control.	• Time-integrated samples are typically collected (e.g., 24-hour samples for residential sites and 8-hour samples for industrial sites). • Combining high-frequency spatial/temporal concentration monitoring with controlling factor monitoring can expedite decision process by reducing the number of field deployments. • Best practice to collect indoor and outdoor air samples simultaneously.
Crawl-Space Air	• Gives concentrations immediately below building and receptors that reside/work within.	• Background sources from overlying building may complicate data interpretation.	Most guidance uses an attenuation factor of 1.0 between crawl space and indoor air.
Cross-Slab Pressure Differential	• Can provide evidence of direction and magnitude of vapor transport (in or out).	• Requires sub-slab port or other subsurface sampling point. • Temporal variations complicate interpretation and often require multiple sampling events.	Detection levels down to 1 pascal can be obtained using inexpensive 0–0.25 inch-water magnahelic gauge.
Barometric Pressure	• Can provide evidence of direction and magnitude of vapor transport.	• Public data sources of barometric pressure may not represent site-specific conditions depending on the location of the weather station.	Data may be downloaded from public sources or obtained from an on-site mobile weather station.
Building Ventilation Rate	• For many commercial buildings, rate is already known from design specifications. • Value can be >10 times default parameters allowed in models.	• For residences, seasonal variations may be large.	Fewer sampling locations are needed if additional mixing of air within building is provided. Most commonly used for commercial receptors.

Measurement	Relative Advantages	Relative Disadvantages	Comments
Compound Specific Isotope Analysis	• Can help distinguish indoor sources from true VI. • Isotopic ratios are independent of concentration; they can provide another line of evidence.	• Some complexity in interpretation. • May be too technical for many stakeholders.	This is essentially a specialized forensic technique, and as such it is typically not pursued until later rounds of an investigation.
Continuous Analyzers	• Provide large amounts of data. • Can help sort out temporal variations and background scatter.	• Can be cost prohibitive for individual household investigations.	Larger data sets allow correlation to other variables such as pressure differentials, wind speed, and HVAC systems.
Soil Physical Properties	• Enable site-specific values to be used in predictive models. • Values can be >10 times default parameters in models.	• Data collected near a building may not be representative of zone beneath building. • Difficult to get rig near most residential buildings (e.g., lawns, landscaping, trees).	Most sensitive soil physical properties to measure are percentage of water content and permeability.
Groundwater Data	• Monitoring wells already exist for many sites (previous data). • Acceptable to most agencies. • Familiar media to most investigators. • Temporal effects minimal.	• Lookup values, attenuation factors, or models tend to be extremely conservative, so VI risk is often overestimated. • Existing data may be from a well that is not optimally screened for upper water table.	This approach is often used as an initial screen.
High Volume Sampling	• Characterizes sub-slab region in large buildings. • Less disruption, reduced costs to traditional grid sampling. • Can collect mitigation design information.	• Can only be done in large buildings. • Modeling is needed to understand leakage through slab.	Good for large buildings >8,000 square feet. Supports retrofit mitigation system design.
Building Pressure Control	• Can enhance advective flow of vapor-forming chemicals into buildings to rapidly evaluate seasonal variation. • Can evaluate contribution from interior sources.	• More difficult on larger or leaky buildings. • Need to understand cross-slab pressure differential range.	Tool for rapid evaluation of indoor air concentrations over large range of conditions.

Notes: HVAC = heating, ventilation, and air conditioning and TCE = trichloroethylene or trichloroethene.

7.8.2.2. Temporal Variability

Short-term temporal variability in subsurface VI occurs in response to changes in weather conditions (temperature, wind, barometric pressure trend, etc.) and precipitation (soil moisture content).

Research shows that short-term variations in soil vapor concentrations are less than a factor of two at depths greater than 5 feet. It was also shown that seasonal variations are less than a factor of five in colder climates (Hartman 2006). Larger variations may be expected in areas of greater temperature variation and during heavy periods of precipitation, as described below.

IBM, Endicott, New York

Data from a large site in Endicott, New York, collected over a 15-month period showed soil vapor concentration variations of less than a factor of 2 at depths greater than 5 feet bgs.

- **Temperature:** Effects on soil vapor concentrations due to changes in the vadose-zone temperature are minimal. The bigger effect is due to changes in the operation of an overlying building's HVAC system or the ventilation of that building by opened doors and windows. In colder climates, this implies concentrations are most likely high in the winter season when ventilation of indoor air is minimal. Research suggests that temporal variations in soil vapor are typically less than a factor of two and that seasonal effects are less than a factor of five (Hubbard and Hagberg 1996; Rose et al. 1990; Washington and Rose 1992; Winkler et al. 2001). If the measured values in soil gas are within a factor of two of allowable risk levels, then repeated sampling may be appropriate. Similarly, if the measured concentrations in indoor air are within a factor of five of allowable risk levels, then repeated sampling may be appropriate.

- **Precipitation:** Infiltration from rainfall can potentially impact soil vapor concentrations by displacing the soil vapor, dissolving VFCs, and by creating a cap above the soil vapor. Infiltration from large storms penetrates only the uppermost vadose zone in many settings. In general, soil vapor samples collected at depths greater than 3–5 feet bgs, under foundations, or under areas with surface cover are unlikely to be significantly affected by precipitation. Soil vapor samples collected closer to the surface (<3 feet) with no surface cover may be affected. If the moisture has penetrated to the sampling zone, it typically can be recognized by difficulty in collecting soil vapor samples. If high vacuum readings are encountered when collecting an active gas sample or drops of moisture are evident in the sampling system or sample, measured values should be considered as minimum values.

- **Barometric Pressure:** Barometric pressure variations are unlikely to have a significant effect on soil vapor concentrations at depths exceeding 3–5 feet bgs unless a major storm front is passing by. A study in Wyoming (Luo et al. 2006) showed little or no relationship between barometric pressure and soil vapor oxygen concentrations.

In summary, temporal variations in soil vapor concentrations, even for northern climates, are minor compared with the conservative nature of the risk-based screening levels. If soil vapor values are a factor of five times below the risk-based screening levels, it is unlikely that repeat sampling will find a concentration in excess of risk-based screening levels unless a major change in conditions occurs at the site (e.g., elevated water table, significant seasonal change in rainfall).

The temporal variability in indoor air samples generally decreases as the duration of the sample increases because the influences tend to average out over longer intervals. Published information on temporal variability has shown that 24-hour indoor air samples typically exhibit concentration ranges within a factor of two to five (Kuehster et al. 2004; McAlary et al. 2002). In contrast, high-frequency continuous monitoring has shown indoor air concentrations ranging up to two orders of magnitude over several hours, often correlating with changes in barometric and differential pressure (Hosangadi et al. 2017).

7.8.2.3. Background Sources

There may be multiple sources of chemicals affecting the overall quality of the indoor air, and those sources may not be associated with the investigated chemical release or may not be entering the indoor air via the VI pathway. That multitude of sources may confound the interpretation of indoor air sample results (Dawson and McAlary 2009) and are typically referred to as background sources. Common background sources include adhesives (automotive, household, craft, plumbing) and adhesive removers, household cleaners, lubricants, bonders, antistatic aerosols, automotive parts and gun cleaners, paint strippers, stain removers for fabrics, jewelry polish, water repellants, spray paints, dry-cleaned materials (e.g., clothing containing residual dry-cleaning solvents), caulks and sealants, cosmetics (e.g., hair spray, nail polish, nail polish remover, and perfume), air fresheners/odor eliminators, and insect repellants. Background sources also include outdoor sources, such as those related to automotive exhaust, smoking (e.g., benzene), commonly emitted solvents (PCE, TCE, etc.), and wildfires. Additional information on background sources is available in the **Background Sources to Indoor Air Fact Sheet**.

When sampling indoor air, field staff should consider the sorptive nature of some materials (e.g., carpeting, drapes, upholstery) to retain VFCs, slowly releasing them to the indoor environment over a period of weeks or more (Boyer 2004; Dawson and McAlary 2009). When dealing with background sources, the following actions may need to be considered:

- Conduct a building walkthrough/survey in advance of an indoor/outdoor air sampling event and note any identified background sources on the building survey form. Examples of building survey forms from multiple state and federal agencies are provided in **Appendix B**. The **Indoor Air Quality Questionnaire and Building Inventory Checklist** is also included with this guidance. This is also a good opportunity to communicate with occupants on VFCs in everyday products (see **Chapter 3: Community Engagement**) and discuss activities that should be avoided if possible immediately before and during sample collection.

- Address sources of background contamination ahead of sampling. This may include not using VFC-containing products at least 24–48 hours before and during the indoor air sampling event or, if practical, remove products from the building 24–48 hours prior to the sampling event. It should be noted, however, that product removal may not be feasible or allowed by a homeowner or business and, even if removed, these products were likely used within the space prior to removal and the presence of VFCs may not dissipate quickly (or at all) after product removal. This may then present a potential false interpretation of indoor air sampling results. It is also often difficult to find and remove all potential background sources (Bingham et al. 2023; Doucette et al. 2010).

- Obtain outdoor air samples when collecting indoor air samples. In this way, outdoor air quality can act as a baseline, to which interior and subsurface sources may be additive.

- Use a targeted site-specific VFC list. The site-specific VFCs may be limited to a few chemicals, which may not be present at significant background levels, so it may be possible to conduct indoor air monitoring for a target list of analytes and avoid complications associated with background contributions.

- Conduct additional sampling techniques such as real-time monitoring (**Real-Time Monitoring Fact Sheet**), BPC testing (**Pressure Monitoring and Building Pressure Control Fact Sheet**), or compound-specific isotope analysis (**Approaches for Vapor-Forming Chemical Source Determination Fact Sheet**).

Evaluating sampling results in an MLE approach to determine background sources to indoor air is discussed in the **Multiple Lines of Evidence Fact Sheet**.

7.9. Per- and Polyfluoroalkyl Substances Considerations

PFAS are a group of thousands of synthetic organofluorine chemical compounds that are used in a variety of commonly used products, including adhesives, waterproof materials, food packaging, cooking surfaces, furniture, fire retardants, and insulation. PFAS have become common VFCs at many sites, with investigations focused on soil, groundwater/surface water, and/or drinking water. Since the early 2010s, strategies for investigating and regulating PFAS in environmental media have rapidly developed both at the state and federal level. For further information regarding PFAS, refer to ITRC's PFAS Guidance document (ITRC 2023).

Recent studies and research have identified several PFAS, including numerous polyfluorinated organic substances (e.g., fluorotelomer alcohol [FTOHs]), as having sufficient vapor pressure (>1 mmHg) and HLCs (>1E-5 atm m^3/mol) to be designated as VFCs. As part of these recent studies, numerous PFAS were collected in the vapor phase for laboratory analysis. As such, it was determined that "volatile PFAS may pose health risks to building occupants" through the VI pathway and warrant "consideration during VI assessments at facilities where high PFAS concentrations are present in shallow soil and groundwater" (Schumacher et al. 2024, 7). Additional research has identified that the application of the thermal desorption GC/MS/MS method should be limited to FTOHs and perfluorooctanesulfonamides, versus using "a parallel solvent extraction approach to quantify the PFCA [perfluoroalkyl carboxylic acid] compounds" (Hayes et al. 2024, 94). For further information regarding PFAS as a VI concern, refer to ITRC's **Vapor-forming Per- and Polyfluoroalkyl Substances (PFAS) Fact Sheet**.

It is evident that PFAS will continue to be a large focus of study with respect to environmental impacts and human toxicity. This will more than likely include future studies about the VI pathway for volatile PFAS. Therefore, PFAS should not be dismissed as impacting only soil and groundwater. When PFAS is present in other media, consideration should be given to assessing the VI pathway. As active areas of PFAS research include volatility, analytical methods, presence/sources in indoor and outdoor air, and transformation, practitioners should not make PFAS a primary focus of VI investigations as of the time when this document is released. Consultants, industry personnel, and regulators should be sure to monitor ongoing research and advancements.

7.9.1. Considerations When Sampling for Per- and Polyfluoroalkyl Substances

Currently, sampling and analytical methods for PFAS in the vapor phase are being developed. Developing these methods without the use of materials that contain PFAS can be challenging, particularly as legacy soil vapor probes have commonly used Teflon tubing. Prior to sampling for PFAS in soil vapor and/or indoor/outdoor air, practitioners should refer to their local agencies for any updated guidance and/or ITRC's PFAS Guidance for materials that should be avoided. For sampling methodologies, practitioners can refer to **Sections 7.2** through **7.4** of this chapter.

7.10. Analytical Methods

7.10.1. Choosing an Appropriate Analytical Method

A variety of analytical methods are available to measure air and soil vapor samples, all of which can give accurate results when followed with appropriate QA/QC. The most common COPCs for VI investigations are VOCs, although specific SVOCs and methane can also be of potential concern. **Table 7-7** summarizes the most common methods.

Table 7-7. Common analytical methods.

Analytes[a]	Method	Sample Media/Storage	Technology[b]	Method holding time	Reporting limit[c]
Volatile Organic Compounds (VOCs)					
BTEX, MTBE, TPH	TO-3	Air sampling bag or canister/ambient temperature	GC/FID	30 days for canister	1–3 µg/m^3
Nonpolar VOCs	TO-14A	Syringe, canister/ambient temperature	GC/ECD/FID(D)ELCD or GC/MS	On-site analysis or up to 30 days (depending on container)	1–3 µg/m^3
Polar and Nonpolar VOCs	TO-15A	Canister/ambient temperature	GC/MS	30 days for canister	1–3 µg/m^3
Low-level VOCs	TO-15 SIM	Canister/ambient temperature	GC/MS	30 days	0.011–0.5 µg/m^3
Polar and Nonpolar VOCs/PAHs	TO-17[d]	Sorbent tube: mono- or multi-bed	GC/MS	30 days	1–3 µg/m^3
VOCs	8021B modified[e]	Syringe, air sampling bag, glass vial/ ambient temperature	GC/PID	On-site analysis or up to 30 days (depending on container)	10–60 µg/m^3
VOCs	8260B modified[e]	Syringe, air sampling bag, glass vial/ ambient temperature	GC/MS	On-site analysis or up to 30 days (depending on container)	50–100 µg/m^3
Semi-volatile Organic Compounds (SVOCs)					
SVOCs	TO-13A[d]	High-volume collection (may require large sample volume, e.g., 300 m^3)/PUF/XAD media, chilled <4°C	GC/MS	Extracted within 7 days of collection and analyzed within 40 days of extraction	5–10 µg/sample
Low-Level PAHs	TO-13A SIM[d]	High-volume collection (may require large sample volume, e.g., 300 m^3)/PUF/XAD media, chilled <4°C	GC/MS	Extracted within 7 days of collection and analyzed within 40 days of extraction	0.5–1 µg/sample
Pesticides and Polychlorinated Biphenyls (PCBs)					
Pesticides and PCBs	TO-4A[d] or TO-10A[d]	High-volume collection (may require large sample volume, e.g., 300 m^3)/PUF media, chilled <4°C	GC/ECD	Extracted within 7 days of collection and analyzed within 40 days of extraction	Pesticides: 0.5–1 µg/sample, PCBs: 1–2 µg/sample
Fixed Gases					
Fixed Gases (methane, nitrogen, oxygen)	ASTM-946 or USEPA 3C	Canister or air sampling bag/ambient temperature	GC/FID	3 days for air sampling bag, 30 days for canister	1–2 mg/m^3

Notes: a. This is not an exhaustive list. Some methods may be more applicable in certain instances. Other proprietary or unpublished methods may also apply. BTEX = benzene, toluene, ethylbenzene, and xylenes; MTBE = methyl tertiary-butyl ether ; PAH = polycyclic aromatic hydrocarbons; PCB = polychlorinated biphenyls ; SVOC = semi-volatile organic compounds; TPH = total petroleum hydrocarbons ; VOC = volatile organic compound ;
b. ECD = electron capture detector, FID = flame ionization detection, GC = gas chromatography, MS = mass spectrometry, PID = photoionization detection, (D)ELCD = (dry) electrolytic conductivity detector, TCD = thermal conductivity detection.
c. Reporting limits are based on an undiluted sample and are compound specific and can depend upon the sample collection and the nature of the sample. Reporting limits shown are for the range of compounds reported by the analytical methods. Further, these are typical, but lower detection levels may be available. Discuss with your laboratory before samples are collected.
d. The indicated methods use a sorbent-based sampling technique. The detection limits will depend on the volume of sample passed through the media.
e. Method is generally applicable only for on-site analysis of soil vapor samples.

The primary criteria for choosing the appropriate method are as follows:

- VFCs
- Concentrations that may be encountered during sampling
- Required reporting limits (RLs) and other DQOs
- Sampling logistics
- Cost

The planning stages of the investigation should include discussions with both the sample collection team and laboratory personnel to ensure that all team members understand how the samples are to be collected and analyzed. Predeployment planning should include arrangements for collecting required field QC samples and ensuring that the laboratory is prepared to supply sampling media not only for all field samples, but also for the field QC samples. It is important to note that QA/QC protocols may vary greatly among laboratories, so the practices should be reviewed and specified in the work plan prior to data collection and field deployment. Data validation methods (when required by the regulatory agency) should also be specified and approved in advance.For example, USEPA Methods TO-14A and TO-15 are commonly used for VOCs in indoor and outdoor air samples because of their ability to achieve very low RLs. Those methods use a GC/MS (or GC/ECD) as the analytical methodology, which includes an MS as the detector. The MS can be operated in two different detection modes: full-scan and SIM. SIM provides enhanced sensitivity. There is a trade-off: the more ions monitored, the less the sensitivity, and a minimum of three ions is typically required for each analyte. There are enhancements in newer MS instruments that reduce this constraint, but there is a practical limit to the balance between the sensitivity and the number of target analytes. As an example, as of this writing SIM typically increases sensitivity by a factor of 5–10 if the list of analytes is long. Some compound selectivity and the ability to identify unknowns may be lost in the use of SIM analysis due to limiting the masses scanned. To surmount this, some laboratories offer to analyze samples using a hybrid method that uses SIM mode for select analytes and scan-mode for everything else. This hybrid is very specialized and must be arranged with the laboratory well in advance of sample collection. As written, TO-15 is performed in the full-scan mode and can analyze for a large list of approximately 70 compounds with RLs ranging from 0.2 to 0.5 ppbv. That analyte list and those RLs are generally more than sufficient when analyzing soil vapor. If SIM is to be employed, that should be agreed upon in advance.

In the modified SIM mode, the greater sensitivity achieves RLs ranging from 0.002 to 0.010 ppbv, but for a smaller list of 12–15 compounds. Because soil vapor samples can exhibit VFCs at higher concentrations than the SIM method is typically calibrated to, the SIM method is appropriate for only indoor and outdoor air samples. Before deciding to use SIM, it is important to recognize that the use of the SIM option is a modification of the method that should be documented and agreed upon by the regulators, data users, and laboratory. Many laboratories do not routinely analyze soil vapor in SIM mode because the high sensitivity of SIM also means that SIM analyses are easily saturated, so it is important to discuss the need for SIM when the laboratory is chosen and then again when the samples are submitted.

7.10.1.1. Sample Containers and Storage

The appropriate sampling vessels/containers for collecting active and passive air and vapor media samples and their acceptable storage methods are presented in **Sections 7.4.1.1** and **7.4.2** of this document. The following subsection provides some additional compound-specific details with regard to these sampling containers.

For fuel-related compounds (BTEX, TPH) and biogenic gases (CH_4, CO_2, O_2), allowable containers include air sampling bags, gas-tight (glass or stainless steel) vials, adsorbents, and passivated (SUMMA) stainless-steel canisters.

For halogenated compounds (e.g., TCE, TCA, PCE), allowable containers must be gas tight but also dark to eliminate potential photo-destructive effects. The walls of a glass container may be an inefficient transmitter of the UV light that leads to photodegradation, but so long as there is some potential for photo-destruction, dark containers should be used when measuring anticipated low concentrations such as those in indoor or outdoor air.

Adsorbents are suitable for most VOCs and SVOCs, but not very volatile compounds, such as CH_4; however, multiple adsorbents may be required to deal with complex mixtures.

See **Table 7-7** for a list of hold times for common analytical methods. Quality Assurance Considerations

QA considerations are crucial when performing VI sampling to ensure the reliability and accuracy of the results. VI, the process by which volatile chemicals from contaminated groundwater or soil enter buildings, requires precise sampling techniques to accurately assess potential health risks. QA procedures help prevent errors and variability in the data by ensuring that sampling equipment is properly calibrated, field protocols are consistently followed, and environmental conditions are appropriately accounted for. Additionally, using QC measures such as duplicates, blanks, and proper chain-of-custody documentation ensures the integrity of the samples and the reliability of the data, ultimately supporting sound decision-making regarding environmental remediation and public health protection. Without thorough QA practices, the risk of obtaining misleading or incorrect results increases, which could delay necessary interventions and lead to inaccurate risk assessments. For more information on QA procedures with respect to VI investigations, refer to the **Quality Assurance Considerations Fact Sheet**.

This portion of the page left blank intentionally. Next chapter begins on the following page.

CHAPTER 8: DATA EVALUATION AND VAPOR INTRUSION RISK ASSESSMENT

8.1. Introduction

Throughout the VI project life cycle (see Figure 2-9), qualitative and quantitative data and VI-pertinent information are gathered to determine whether there is a current or future VI exposure pathway and to understand the implications if such pathways exist. The evaluation of these pathways typically includes comparison of site data to concentrations based on regulatory risk thresholds through screening or risk assessment. The VI project life cycle typically starts with screening (see Chapter 5: Site Screening) to eliminate low-risk sites from further consideration. Sites that are not eliminated at the screening step are addressed using more site-specific considerations to determine whether there might be a VI risk and to make site management decisions.

This chapter assumes that site screening for the VI pathway determined that further data collection (see Chapter 7: Sampling and Analysis) was warranted and that an investigation strategy (see Chapter 6: Iterative Investigation Process) was chosen, designed, and implemented. It provides a framework to evaluate the resulting data and describes approaches to assess VI risk, ranging from simply applying generic/default screening levels to conducting site-specific risk assessments.

These evaluation methods can be used to (1) make a sound, technically defensible determination as to whether the VI pathway is complete (or is incomplete and warrants no further investigation); (2) evaluate the potential risk associated with pathways that are found to be complete; and (3) inform decision-making about next steps, such as further investigation, remediation, or mitigation.

Although this chapter focuses on data collected for site investigation, the concepts also apply to data collected during other stages of the VI life cycle (e.g., mitigation, site management).

It is also important to note that as part of the VI project life cycle, the potential for acute exposure of building occupants to contaminants from the VI pathway should be considered whenever additional data are obtained (see Sections 5.2.3 and 10.1). In addition, many state and federal agencies will allow a responsible party to implement a remedial action to address VI at any point in the process, even prior to confirming the pathway is complete. This proactive approach can be viewed as responsive to the concerns of public health. This is often more economical prior to construction of new buildings. Alternatively, the decision may be made to conduct long-term monitoring, particularly for undeveloped parcels, until such time as the vapor source is remediated or a future development will introduce receptors (people) who could be exposed to potential VI.

The following sections of this chapter discuss essential components of the data evaluation process (Section 8.2), approaches to assessing VI risk including use of screening levels (Section 8.3), screening risk assessments (Section 8.4), site-specific screening levels (Section 8.5), and site-specific risk assessments (Section 8.6). Cleanup levels are also discussed (Section 8.7).

8.2. Data Evaluation

The state of the science related to VI assessment and mitigation has evolved considerably over the past few decades. There have been substantial changes in the overall understanding of the variables influencing migration of VFCs in the subsurface, evolution of sampling methodologies and best practices, screening levels, and regulatory guidance documents. Staying up to date with current practices is critical to reduce uncertainties and produce usable data. Chapter 7: Sampling and Analysis summarizes a wide

variety of tools and methods used to gather VI-related data, along with data quality considerations for each.

The process for evaluating data—qualitative or quantitative—and other VI-related information from a site or building includes several steps:

- Verifying data meet DQOs for the intended use
- Confirming adequacy of data to support decision-making
- Confirming common data management errors have been avoided
- Evaluating the collected data for consistency with the CSM (including exposure scenarios and other assumptions) and updating the CSM if needed
- Comparing concentration results with risk-based concentrations
- Using MLE to interpret the data and help decide what to do next (see the **Multiple Lines of Evidence Fact Sheet**)

8.2.1. Data Quality Review

A variety of field and laboratory data and other information is collected during the life cycle of a VI project, including quantitative data (e.g., chemical concentrations), qualitative or semiquantitative data (e.g., weather conditions, differential pressure, parameters from sample screening in the field), and a range of site-specific observations. Before using the results, the available data should be reviewed for quality and adequacy so that the user understands potential limitations. This review relies on early project planning that involves developing site-specific DQOs, although the level of detail in written plans may vary. After the data are collected, the data quality review is largely a process of confirming that planned data collection and sample analysis steps were executed as expected, or that caveats are understood and acceptable.

8.2.1.1. Quality Data

Due to the inherent limitations of environmental sampling and analysis methods, including those associated with VI assessments, data should be reviewed before use to determine whether they meet project-specific DQOs. A range of DQOs will often be specified for a given project that will drive the selection of field and laboratory sampling and analysis procedures and methods to ensure, for example, that method reporting limits will be appropriate for comparison to regulatory screening levels or for site-specific risk assessment. These are typically specified in a QAPP or sampling and analysis plan that is developed during the project planning phase (NJDEP 2014; USEPA 2006c). See the **Data Quality and Adequacy Fact Sheet** for more information. Procedures for addressing data quality for common chemical analytes that are reported by a laboratory are well established (see **Section 7.10.2**). For quantitative data (e.g., results from laboratory analyses), data validation often considers the parameters of precision, accuracy, representativeness, comparability, completeness, and sensitivity of the data and is performed to identify specific QC nonconformances. In certain cases, project-specific DQOs may extend to a range of field measurements relevant to VI assessments and site-specific observations, including field-screening methods. **Chapter 7: Sampling and Analysis** includes data quality considerations specific to various tools and methods used for VI studies. In addition, the state or other jurisdiction overseeing the VI assessment often provide guidance on data quality–related expectations and validation procedures.

The data usability evaluation considers the introduction of bias or other effects these QC nonconformances may have on the interpretation and use of the data.

8.2.1.2. Adequate Data

The amount and type of information and data available for each site and/or building will vary. Before using data collected as part of the VI investigation, it must be determined whether there is sufficient information to support site management decision-making, including additional investigation, monitoring, mitigation, remediation, and no further action. An initial check is to verify that planned samples and information were collected and that the rationale for any exceptions is understood. Another check on data sufficiency is to verify that common VI investigation limitations were accounted for (e.g., see Section 7.8.2). As part of this data review, the following should also be considered:

- Was spatial variability considered (see Section 7.8.2.1)?
- Was temporal variability considered? For example, VI sampling would usually need to be conducted during various seasons (e.g., cold and hot seasons, wet and dry seasons) (see Section 7.8.2.2).
- Have soil vapor and indoor air samples been collected during the worst-case season or condition (see Section 7.8.2.2)?
- Have background sources been considered (see Section 7.8.2.3 and the Background Sources to Indoor Air Fact Sheet)?
- Has the VI potential been assessed at all buildings that may be affected? This can include buildings near the source release area or the footprint of the groundwater plume, as well as buildings that may be affected by conduit or vertical VIPPs (see the Vapor Intrusion Preferential Pathways Fact Sheet).

In addition, some regulatory authorities have specific guidance on the type and number of samples to collect, for example, the number of sub-slab samples to collect for a given building size or the need to sample in more than one season (see Appendix A: Summary of State VI Practices). Because of these complexities, a site or building may need more than one round of testing before site management decisions can be made.

8.2.1.3. Common Data Evaluation Problems

Common mistakes in VI evaluations, investigations, and mitigation are highlighted in the Common Mistakes in Vapor Intrusion Evaluations, Investigations, and Mitigation Fact Sheet. One frequent problem is related to inconsistent units and unit conversions. Commonly reported units of air and soil vapor samples are micrograms per cubic meter ($\mu g/m^3$), parts per billion volume (ppbv), parts per million volume (ppmv), micrograms per liter (µg/L), and percent (%). Conversions between these units often depend on molecular weight and other factors. See the Units and Unit Conversions Fact Sheet for details.

8.2.2. Key Data Evaluation Steps

8.2.2.1. Compare Data to Conceptual Site Model

Before evaluating analytical results and other data to understand potential VI risk, a data quality review should be done, as discussed in Section 8.2.1; see also the Reviewing Soil Vapor Data Checklist. Once the quality and adequacy of the data set is understood, it is helpful to compare the results to expectations based on the CSM. Unexpected results could point to other potential problems such as canister contamination (McHugh et al. 2018), field sampling errors (e.g., mislabeling samples in the field), contaminant migration, or previously unknown sources. These are issues that may or may not have been identified in the data quality review. Verification testing may have to be implemented to address unexpected or unexplainable data.

Exposure assumptions (e.g., residential vs. commercial/industrial, building occupancy and use) should also be confirmed in this step to document that the CSM is consistent with field observations.

8.2.2.2. Compare Concentration Data to Risk-Based Levels or Conduct a Risk Assessment

The site screening and data evaluation stages of the VI life cycle require the use of various decision-making tools to assess the potential for human health risks. For example, in the site screening steps, existing site groundwater data can be compared to generic screening levels (see **Screening Levels Fact Sheet**) as a means of evaluating whether sub-slab soil vapor and/or indoor air samples should be collected. Similarly, as part of the data evaluation step, sub-slab data can either be compared to generic screening levels or used in a predictive model to determine whether indoor air samples should be collected or mitigation measures should be implemented.

State-Specific Approaches

Commonly, the regulatory framework applicable to a project will determine the type of actions that will be needed. The approach may vary substantially from one jurisdiction to the next. For example, Michigan defines expected outcomes on the basis of sub-slab soil gas (SSSG) data (MDEQ 2013b, Table 5-3). A handful of states and USEPA regions use a VI risk management **decision matrix–type approach** to determine the necessary actions on the basis of both the indoor air and SSSG concentrations or the magnitude of these concentrations relative to applicable screening levels (e.g., MDE 2019, Figure 1; NHDES 2013, Table 2; NYSDOH 2006b, Section 3.4; NYSDOH 2024; USEPA 2017c; USEPA 2020, Tables 8-1 and 8-2; WDNR 2018, Table 7a).

In the early stages of a project, generic screening levels are often used as a point of comparison for site concentration data. The use of generic screening levels is described in **Section 8.3** below. In some cases, a generic screening risk assessment can be done to provide an initial indication of potential site risks. This could be beneficial if, for example, concentrations are below or just above the generic screening levels (see **Section 8.4**). Site-specific screening levels may also be calculated and are typically less conservative than generic screening levels (see **Section 8.5**). Site-specific risk assessments may also be appropriate (see **Section 8.6**).

Sections 8.3 to **8.6** describe comparison values and risk assessment approaches typically used to make site management decisions (e.g., additional investigation, monitoring). If VI mitigation is needed, site- or building-specific cleanup levels may need to be developed (**Section 8.7**).

The regulatory agency should be consulted prior to selecting the risk-based approach or making decisions from the data evaluation steps. For industrial sites, OSHA-acceptable workplace levels (e.g., permissible exposure levels or other acceptable workplace levels may be applicable as indoor air target concentrations, depending on the circumstances and established policies of the regulatory agency. As previously stated, the oversight regulatory agency should be consulted when determining any value or other actions at sites within their oversight.

8.2.2.3. Use Multiple Lines of Evidence

As discussed in **Section 8.2.2.2** above, most investigation strategies include use of some form of concentration-based comparison to understand potential risk associated with VI at a given site. MLEs look at additional evidence to confirm and support that VI is occurring. Simply put, if site concentrations exceed the comparison value, additional data collection and/or data evaluation may be needed for VI risk-based decision-making. For a more detailed discussion of MLE including definitions, types, and use, please refer to the **Multiple Lines of Evidence Fact Sheet**.

Comparison of site sample results to concentration thresholds alone, however, is often overly simplistic. A number of confounding factors serve to complicate VI data sets. For example, VFCs emitted from common consumer products could result in detections of certain chemicals such as PCE, TCE, or

benzene in indoor air samples. Indoor air may also be affected by VFCs found in outdoor air. Relying on indoor air alone, therefore, could lead to an incorrect interpretation that VI is occurring when it is not.

When evaluating complex relationships between groundwater, soil, soil vapor, indoor air, and the built environment (i.e., human-made surroundings), decisions cannot often be made on any single, simple fact, procedure, data point, data type, or data comparison. Any piece of information that improves understanding of the potential pathway, the risk to receptor from VI, and management of the site can be thought of as a LOE. To evaluate site data or to address uncertainty, MLE may be needed to improve confidence in data interpretations. The MLE approach puts together various pieces of information from the site or building that have been observed, collected, or evaluated and uses them to answer site-specific VI questions. See the **Multiple Lines of Evidence Fact Sheet** for examples of VI questions typically answered using the MLE approach and keep the following considerations in mind when using the MLE approach:

- Not all MLE need to be used for all sites or buildings. It is common for practitioners to select a subset of MLE that are most applicable to site-specific conditions (e.g., prioritize MLE and data collected in close proximity to the building of interest or proposed location of a future building) and ones that help to answer the questions being asked and/or to respond to a state's regulatory framework.
- Site-specific conditions and the site CSM will help to determine the relative importance of each MLE.
- The use of many MLE may not be required if only a few, or even one, provide clear evidence to answer the VI question being asked or support VI management decisions.
- LOEs with higher degrees of certainty and relevance will potentially have greater impact and weight in the MLE approach than LOEs with lower degree of certainty.
- All MLE may not be in concordance; this should be evaluated and explained. The CSM should also be refined based on new information and/or LOE.
- Decisions should be made in consultation with the regulatory agency and based on what professional judgment deems to be reasonable and practical for the specific site. Regulatory frameworks from individual states may limit the ability to use some LOE.

To illustrate the MLE approach, **Table 8-1** provides a short list of example LOEs and how they may be used to help understand whether measured indoor air concentrations are derived from subsurface or background sources. Details on the MLE approach and additional examples are provided in the **Multiple Lines of Evidence Fact Sheet**. The MLE approach is also useful in approaches used to characterize chemical sources. Traditional environmental site investigations focus on the nature and extent of contamination as determined by common methodologies developed to provide data for regulatory purposes, but other more sophisticated analytical techniques can produce source-specific chemical fingerprints. See the **Approaches for Vapor-Forming Chemical Source Determination Fact Sheet** for information on these data evaluation techniques.

Table 8-1. Example lines of evidence to help distinguish between subsurface and background sources of vapor-forming chemicals in indoor air.

Line of Evidence	Uses
Chemicals of Potential Concern (COPC): The easiest and probably most important line of evidence is the identification of COPCs at the site.	Provided sufficient characterization has occurred, the investigator should be able to establish the principal contaminants associated with the original discharge or spill. Using this information, along with any degradation products related to these chemicals, the COPCs can be identified. Thus, an investigator can limit the scope of the data evaluation and the analytes for future sampling events.
Building Construction and Current Condition: Information regarding the construction and conditions (e.g., heating, ventilation, and air conditioning [HVAC] system location and operation; building activities; hours of building occupancy) of a building may be used to establish the likelihood of subsurface soil vapor entering.	For example, if a building's HVAC system generates positive air pressure within the building, it may be reasonable to conclude that this system will minimize or prevent soil vapor from migrating into the building from a subsurface source. Other building factors that should be considered are date of construction; foundation and slab type; condition of foundation and extent of cracks/seams and floor penetrations; building materials; chemical use in the building; the presence of sumps, perimeter drains, and elevators; utility conduits; the height of buildings (particularly in cold climates); basement details; crawl spaces; vapor barriers or radon mitigation systems; and surface cover outside the building. Facts regarding the building construction and current condition may help with assessing the potential for soil vapor contamination to migrate into a building.
Sub-Slab Data: Soil vapor measurements collected from beneath a building will provide a good indication of what vapor-forming chemicals (VFCs) may potentially migrate to indoor air.	If VFC concentrations in the sub-slab vapor samples are similar to or lower than indoor air concentrations in the building, it is reasonable to conclude that the measured chemical in the indoor air sample is derived in part from other background sources. The difficulty with this line of evidence is understanding the representativeness of the soil vapor samples collected from beneath the building, given spatial variability that is often observed (see **Section 7.8.2.1**). Since soil vapor naturally attenuates to some degree in the migration from the subsurface into an overlying building, detection of a chemical in the sub-slab vapor sample supports, but does not necessarily confirm, that the chemical observed in indoor air is attributable to the subsurface source. Barometric pressure fluctuations can cause reversible vapor flow and can contribute vapors from interior sources to sub-slab samples. Thus, other lines of evidence, such as deeper soil vapor samples, may be important to evaluate to establish the presence of concentration gradients inside and outside the building.

Line of Evidence	Uses
Constituent Ratios: Evaluating the ratio between concentrations of different VFCs in groundwater, soil vapor, sub-slab, and/or indoor air may help to identify potential vapor intrusion contributions or to screen out background sources.	For many VFCs, the background concentration ratios are distinct from groundwater-derived volatile chemical ratios. This characteristic allows the volatile chemical ratios from other media to be used to eliminate indoor air constituents. It is possible that, even if the ratio analysis suggests that indoor or outdoor sources are likely responsible for some of the measured indoor air concentrations, subsurface sources may still be contributing to indoor air concentrations. Conversely, if the ratios of constituents in the indoor air sample are similar to the ratios observed in the sub-slab vapor sample, one may conclude that the two are linked and that there is a contribution from subsurface sources, especially if subsurface concentrations are significantly higher than indoor air concentrations. Comparison of chemical ratios in groundwater to ratios in indoor air may also be considered. These ratios should be adjusted for different relative volatilities of the VFCs using their Henry's Law constants and, if significant, different rates of retardation and/or biodegradation in the vadose zone. The comparison of soil vapor ratios to Henry's Law–adjusted groundwater ratios may be another line of evidence for assessing background contributions or vadose-zone sources. It should be recognized that background sources might result in ratios that fall within the range predicted for groundwater or measured in soil vapor data. Although a constituent ratio analysis can identify obvious background sources, this line of evidence may not necessarily confirm vapor intrusion or eliminate the potential for background contributions.
Presence of Marker Chemicals in Indoor Air: Identification of indicators, such as 1,1-DCE, cis-1,2-DCE, or vinyl chloride in subsurface sources may be used to establish the likelihood for vapor intrusion.	The presence of chemicals that are associated with subsurface contamination but not typical background air sources in indoor air samples is a good indication that vapor intrusion is occurring and that the observed chemicals may be derived from the subsurface. The converse assumption may also be true—the absence of a marker chemical in indoor air samples is a good indicator that little to no contamination is coming from the subsurface, suggesting that indoor air VFCs observed are from background sources. This second assumption will depend on the relative abundance, volatility, diffusivity, and reporting limit of the marker chemical compared to other VFCs.
Spatial Correlation: Spatial distribution of chemicals in a building may assist with identifying the vapor source.	The spatial distribution of VFCs measured within a building may also help with the identification of the source of the vapor. For instance, concentration gradients or hot spots may indicate indoor air sources. The results of air samples taken in various parts of a building can be reviewed and compared to assess whether there are any contaminant concentration gradients or hot spots among the various floors or rooms in a building. In general, if basement concentrations are elevated above background and there is a decreasing contamination gradient from the source (e.g., basement) area to upper floors, there is a relatively good chance that detected concentrations are due to a subsurface source of contamination. It is also possible that other sources (e.g., stored products) may be present in the basement and possibly even in the living area, potentially confounding site-related concentration gradients. For example, use of COPC VFC ratios might eliminate a number of outlier chemicals from background sources but still leave buildings with other COPC VFC ratios that are consistent with either vapor intrusion or a background source. Spatial analysis might show that a cluster of such ratios is consistent with a groundwater plume, whereas in other areas of the building the ratios appear to be randomly distributed and are more likely associated with background levels. Also, if the outdoor data reveal measurable concentrations of multiple chemicals, compare the outdoor concentration ratios to VFCs in indoor air and subsurface soil vapor samples.

8.2.3. Outcomes of the Data Evaluation Process

Ultimately, site management decisions will rely on MLE including comparison of data to generic and/or site-specific screening levels, predictive modeling where applicable, and/or a risk assessment. VI investigations can often be iterative. Upon execution of the work plan and review of the results, the investigator determines whether the site has been adequately characterized and whether the following questions have been addressed:

- Have the nature and extent of VFCs been properly delineated?
- Has the potential for VI at possibly affected buildings been assessed?
- Are there sufficient data to reach a site management decision at the site or to determine that no further actions to address the VI pathway are needed?

If the answers to these and similar questions are yes, the investigator can move on to consider whether mitigation or remediation is warranted.

If the evaluation of the investigative results identifies data gaps that prevent reaching a conclusion at the site/building, additional investigations may be warranted. To expedite this iterative process, supplemental stages of investigation can be built into the original work plan to avoid delays while new work plans are developed and approved by the regulatory agency, if applicable. For example, a standard investigative approach can be developed for assessing VI at each building at a site where a large number of buildings may be impacted. This way, the initial investigation can center on the buildings closest to sources, with subsequent rounds of sampling targeting adjacent buildings (i.e., the step-out process). Keep in mind that subsequent work plans can focus on the scope of work and reference previously approved methods.

8.3. Generic or Default Screening Levels

This section describes how to use generic screening levels in data evaluation. These levels are also known as *default* or *regulatory* screening levels and are typically published by regulatory authorities in lookup table formats.

During the site screening phase, generic screening levels (e.g., for soil vapor or groundwater) are often used to evaluate whether the potential exists for subsurface contaminants to be present in indoor air at levels that could result in adverse health effects to exposed receptors. If each of the observed chemical concentrations are below these screening levels, then significant human health risks would generally not be expected, and further assessment is not needed. The regulatory authority may have guidance on recommended techniques to determine representative concentrations (e.g., maximum, point-by-point, average) for use in this comparison. Such VI evaluations and their conclusions should be based on an adequate data set, with sufficient and reliable data (Section 8.2.1), and be supported by MLE.

While concentrations below an applicable regulatory screening level may indicate the absence of a human health risk under many circumstances, the presence of chemical concentrations exceeding these screening levels does not necessarily mean that unacceptable human health risk exists. Because regulatory screening levels are developed to be conservative (i.e., health protective) and generic (i.e., applicable under many circumstances), an exceedance could simply be an indication that further site-specific evaluation is needed. For example, if a review of groundwater or exterior soil vapor data resulted in an exceedance of the applicable screening level, it may be appropriate to collect sub-slab or indoor air samples for further evaluation. Media-specific considerations and next steps may be best determined by consulting applicable federal or state guidance that applies to a site.

Many state and federal agencies have developed screening levels for various media related to VI. See the Screening Levels Fact Sheet for additional discussion, or Appendix A: State Practices Summary.

8.4. Screening Risk Assessment

Risk assessment is a systematic process used to evaluate the potential health risks associated with exposure to environmental hazards (USEPA 1989). As a starting point for risk assessment, screening levels can be used to conduct a screening risk assessment, and the results can be used to assess whether more refined assumptions are appropriate. A screening risk assessment is a conservative assessment of potential risk and can be used where risk assessment in general is requested or required.

Screening levels are used to calculate risks based on exposure point concentrations for multiple VFCs. This is in contrast to the site screening, which focuses on whether individual chemical concentrations are above, at, or below an applicable screening level.

Functionally, using screening levels to calculate risks achieves the same end result as if the same exposure assumptions were employed in a site-specific risk assessment—in a screening risk assessment, the exposure parameters and toxicity values are already incorporated into the screening levels, so it is not necessary to identify these separately as part of the risk assessment process.

The concept of a screening risk assessment is to incorporate conservative risk assessment assumptions and parameters and to use default/generic values to the extent possible, which then provides an overall conservative estimate of risk. This approach has the following benefits:

- Generally straightforward to implement because generic screening levels are typically available to perform the risk calculations.
- Provides a conservative estimate of risk.
- Simplified approach with only two variables—screening levels and exposure point concentrations—and does not incorporate any site-specific considerations.
- Risk communication can focus more on VI concepts and potential risks when fewer variables need explanation.

This approach has the following applications:

- It can provide an initial indication of potential site risks, as a step further than comparing site data to screening levels, particularly when there are multiple COPCs at concentrations near screening-level concentrations.
- It can be used to conduct a conservative risk assessment.

The risk assessment framework that is presented herein is generally consistent with risk assessment approaches as identified by USEPA's *Risk Assessment Guidance for Superfund, Part A* (USEPA 1989) and USEPA's *Supplemental Guidance for Inhalation Risk Assessment Part F* (USEPA 2009). If a risk assessment is being conducted under a state program, the applicable VI or risk assessment guidance should be consulted. Depending on the regulatory framework applicable to the site, a screening risk assessment may not be necessary if all concentrations in the site media are well below applicable screening levels. On the other hand, if there are complete exposure pathways other than VI, the VI health risks must be considered cumulatively with health risks from other exposures.

To perform a robust screening risk assessment, it is assumed that a site has an adequate data set, as discussed in Section 8.2.1. The following subsections discuss how to conduct a screening risk assessment and how to interpret the results.

8.4.1. Exposure

Because the screening risk assessment uses screening levels directly, the exposure scenarios considered in the evaluation would be limited to those for which screening levels are available. In most cases, these scenarios would be resident or commercial/industrial worker exposure scenarios. (see the Screening Levels Fact Sheet for more information on the derivation of default/generic screening levels). In addition, the exposure pathway that is considered by the screening levels is solely inhalation of air.

If the default exposure scenarios are not realistic for a site, then site-specific information can be considered (See Sections 8.5 and 8.6). Screening levels for a given medium can be used to perform a risk assessment for that medium, since the screening levels already incorporate the exposure assumptions relevant to that given medium and hypothetical receptor and toxicity information relevant to that specific chemical. For example, soil vapor screening levels can be used to evaluate potential inhalation exposure because those screening levels incorporate an AF that assumes a certain degree of attenuation from soil vapor into indoor air (see the Screening Levels Fact Sheet and Attenuation Factors Fact Sheet for more information on AFs for soil vapor).

8.4.2. Inputs and Methods

To perform a screening risk assessment, the inputs are the screening levels and medium-specific concentrations. As mentioned in Section 8.4.1, the screening levels identified for the evaluation should be consistent with the medium or media being evaluated and published by the relevant regulatory agency.

- For federal-led screening-level risk assessments, the residential or industrial air Regional Screening Levels (USEPA 2024a) can be used in a screening risk assessment (see the Vapor Intrusion Screening Levels Calculator Fact Sheet and Screening Levels Fact Sheet for more information).
- As a state example, the DTSC HERO Note 3 Screening Levels (California DTSC 2019) or the environmental screening levels (SFBRWQCB 2019) can be used to conduct a screening risk assessment).

One key point about performing a screening risk evaluation is that screening levels should be obtained for both non-cancer and cancer-based risk screening. When comparing concentrations to a single screening level, the lowest screening level calculated for a non-cancer and cancer endpoint would be used to provide a conservative approach (Section 8.3; see also the Screening Levels Fact Sheet). For a screening risk assessment, both non-cancer hazard and cancer risk are calculated; therefore, both non-cancer and cancer-based screening levels are relevant and used. In almost all cases, chemicals have non-cancer screening levels, and chemicals identified as carcinogenic by the relevant regulatory agency will also have cancer-based screening levels.

With respect to concentration, as mentioned in Section 8.2, using the screening risk assessment process includes an assumption that the available data set is adequate for the task of conducting a risk assessment. This would typically suggest that multiple data points are available to include in the evaluation. The risk assessment can be conducted on a point-by-point basis (e.g., for individual air sampling events for an individual sampling point); however, typically in risk assessment, some degree of data reduction is performed to streamline the evaluation.

These steps generally would consist of (1) identifying chemicals in the given medium that are considered site- and VI-related (i.e., COPCs); (2) identifying exposure points, which are the specific locations at which

receptors may be exposed; and (3) calculating exposure point concentrations, which are the concentrations to which the receptors may be exposed.

For a screening risk assessment that is conducted with a more conservative approach, one option would be to include all VFCs detected in the medium regardless of provenance. This would not include consideration of whether chemicals are present due to potential background or indoor sources. To provide greater context for the screening risk assessment results, it may be helpful to also present the estimated risks for VFCs that are present due to background sources. Chemicals can also be screened as COPCs using screening levels. As mentioned, for direct comparisons, the lower of the non-cancer and cancer-based screening levels is used, and if the maximum detected concentration of a chemical is below that screening level, then, depending on the regulatory guidance or requirements, this chemical may be screened out of the risk assessment and not further evaluated. MLE are available for evaluating VFCs as COPCs in risk assessments, and these are discussed further in **Section 8.2.2.3** and the **Multiple Lines of Evidence Fact Sheet**.

The next step in the process is to identify exposure points. Similarly to COPC selection, a conservative approach in a screening risk assessment could include evaluating each sample location as a separate exposure point. This represents an assumption that the given receptor is present in that location consistent with the exposure parameters used in the development of the associated screening level, or to address uncertainty as to which results are most representative, the results are evaluated independently. If there are multiple indoor air sampling locations within, for example, one specific residence or one commercial building, it may be feasible to evaluate it as one single exposure point, depending on how the locations are used (e.g., if a sampling location is a specific office, that may be reasonable as a separate exposure point; if there are multiple sampling locations within a larger commercial space, then there could be a potential justification for evaluating these as one exposure point). For soil vapor, the considerations are similar—soil vapor can be evaluated on a point-by-point basis (this could be a useful approach for vacant sites, for example, where future buildings are unknown), or using some spatial combination of soil vapor locations. For example, soil vapor locations within or around a specific building could be combined as an exposure point.

For each exposure point, a concentration is needed for use as the basis for the screening risk assessment. A conservative approach would be using a maximum detected concentration for each COPC for each exposure point. In this respect, even if multiple sampling locations are combined into an exposure point, the exposure point concentration would represent a worst-case exposure as it assumes a person is exposed to the maximum concentrations of the COPCs for the sampling points for the entirety of the exposure duration. For VI risk evaluation, exposure point concentrations can also consider both temporal and spatial considerations. Spatially, as discussed under exposure points, concentrations could be combined across sampling locations. In addition, if data are available from multiple sampling events over time, those data could also be combined. With a combined data set, the most common approach to determine an exposure point concentration is to calculate a 95^{th} percentile upper confidence limit on the mean, or 95UCL, which would provide a conservative upper-bound estimate of an average concentration in that medium. 95UCLs can be calculated using USEPA's ProUCL software provided the size and characteristics of the data set meet the assumptions of the statistical tests (USEPA 2022).

Once the screening levels and exposure point concentrations are identified, then the risk calculations can be conducted. For a screening risk assessment, the final piece of information that is needed is the risk target or basis that was used to calculate the screening level. For example, for a cancer-based screening level, this would typically be a cancer risk of 1×10^{-6} (or 1 in 1,000,000) or 1×10^{-5} (or 1 in 100,000), and for non-cancer-based screening levels, this would usually be a hazard quotient (HQ) of 0.1 or 1.

The screening risk calculation is as follows:

$$Hazard\ quotient\ (HQ)\ =\ \frac{EPC\ x\ THQ}{SLnc}$$

$$Cancer\ risk\ =\ \frac{EPC\ x\ TR}{SLc}$$

Where:

EPC = exposure point concentration
THQ = target hazard quotient
TR = target risk
SL = screening level, cancer (SLc) or non-cancer (SLnc)

These relationships depend on the EPC and the SL having the same units, such as µg/m^3 or ppbv. As long as the EPC and the SL are in the same units, these equations can be applied. For further discussion of units, please see the **Units and Unit Conversions Fact Sheet**.

8.4.3. Results

Cumulative cancer risk and the non-cancer hazard index (HI) are the sums of the cancer risks and HQs for all COPCs, as follows:

$$Hazard\ index\ (HI)\ =\ \Sigma\ HQ_{1\ldots i}$$

$$Total\ cancer\ risk\ =\ \Sigma\ cancer\ risk_{1\ldots i}$$

Cancer risk values are described as incremental risks, so a cancer risk of 1×10^{-6} corresponds to an increase in cancer risk of 1 in 1,000,000. HIs are based on a threshold of 1 below which adverse effects are considered unlikely. If the HI is greater than 1, then HIs should be recalculated as the sums of the HQs for COPCs with common target organs. HIs for individual target organs greater than 1 would then serve as the basis for identifying potential adverse effects from exposure to noncarcinogenic VFCs.

8.4.4. Interpretation and Multiple Lines of Evidence

Cancer risk and HI are interpreted based on the regulatory risk thresholds that are applicable to a site. Various demarcations of acceptable risk have been established by regulatory agencies. The National Oil and Hazardous Substances Pollution Contingency Plan (NCP; 40 CFR 300) indicates that lifetime incremental cancer risks posed by a site should not exceed a range of 1 in 1,000,000 (1×10^{-6}) to 1 in 10,000 (1×10^{-4}), and noncarcinogenic chemicals should not be present at levels expected to cause adverse health effects (i.e., an HI greater than 1). Depending on the regulatory framework, cancer risks in the range of 1×10^{-6} to 1×10^{-4} may be considered acceptable, with cancer risks less than 1×10^{-6} considered de minimis. USEPA risk assessment guidance also states that the upper boundary of the risk management range is not a discrete line at 1×10^{-4}; however, USEPA routinely interprets the value of 10^{-4} (as presented in the NCP) to mean 1×10^{-4} in making risk management decisions (USEPA 1991). Additional evaluation of risks that are around the upper end at 10^{-4} may be considered on a site-specific basis; however, acceptance of risk above 1×10^{-4} may vary by regulatory oversight agencies. Screening risk results below these levels typically do not warrant further evaluation or action to be taken. Values above these levels may warrant further evaluation (e.g., additional LOE evaluation, determination of site-specific screening levels, a site-specific risk assessment, risk management, or mitigation/remediation). It is important to note that the thresholds for further evaluation/action vary by regulatory authority (e.g., some states use a cancer risk threshold of 1×10^{-5}, and many states do not use a formal risk assessment process).

Additional interpretation of the screening risk assessment may also help understand and provide context for the results. For example, some questions that could be asked may include the following:

- What are the VFCs that are contributing the most to the cancer risk and/or HI?
    - This can be determined by looking at chemical-specific risks/hazards and identifying the highest values.
- Is the presence of this/these VFC(s) likely attributable to VI (assumes all chemicals detected are included in the screening risk assessment)?

The MLE approach can be used to answer the second question. **Section 8.2.2.3** and the **Multiple Lines of Evidence Fact Sheet** provide information on interpreting the results of a screening risk assessment in the context of the site CSM and other MLE.

8.5. Site-Specific Screening Levels

This section describes how site-specific screening levels are developed and used.

Generic VI screening levels are intentionally conservative, relying on default input values for chemical exposures and vapor migration, to avoid underestimating risk. Therefore, in addition to generic screening levels, some regulatory agencies allow the implementation of a site-specific approach in which generic screening levels can be modified using site-specific soil and building parameters and/or models to obtain screening levels that are more reflective of site-specific conditions (California DTSC 2024; Health Canada 2023; MassDEP 2016; USEPA 2015a). These site-specific screening levels are typically less conservative than generic screening levels. Site-specific inputs can include physical characteristics (e.g., site conditions, building characteristics, etc.) and exposure assumptions (e.g., exposure frequency, exposure duration, exposure time). Other site-specific parameters may also include soil type, groundwater temperature, and background VFC levels in outdoor air. AFs used to derive subsurface screening levels may also be adjusted or used to obtain site-specific cleanup levels for remediation in certain cases using values derived from field measurements (McAlary, Wertz, et al. 2018; McHugh et al. 2012; Nicholson et al. 2021) or transport modeling (API 2012b [BioVapor]; Johnson and Ettinger 1991 [J&E model]; USEPA 2016 [PVIScreen]). In some cases, an odor threshold that is lower than the indoor air risk-based concentration for a chemical can be selected as a screening level (such as concentrations in indoor air at which 50% of the population can detect its odor, if applicable (NHDES 2013).

The following subsections discuss how the following certain specific elements can be integrated into the calculation of site-specific screening levels: alternate receptors and exposure parameters, background indoor air concentrations, AFs, and modeling. Site-specific screening levels are typically calculated for groundwater, soil vapor, or indoor air. For information about screening levels as a general topic, see the **Screening Levels Fact Sheet**.

Site-specific screening levels are applied, evaluated, and interpreted in the same manner as generic screening levels. As such, this section discusses only the site-specific modifications to screening levels; for information on evaluation and interpretation, see **Section 8.4**.

8.5.1. Alternative Receptors and Exposure Parameters

Site-specific screening levels for any medium can be considered for sites or buildings where the current or future occupancy scenario varies substantially from the default exposure scenarios that are typically used to calculate generic or default screening levels, which are most often residential and commercial/industrial scenarios.

Receptors are defined as people who may be exposed to chemicals in indoor air. The identification of potential receptors should be part of the CSM process (see **Chapter 4: Conceptual Site Model**). As mentioned above, typical receptors addressed by regulatory default screening levels include adults and children exposed in a residential setting and adults exposed in an occupational environment. Other site-specific exposure scenarios (e.g., schools, day-care facilities, recreational facilities, industrial buildings such as warehouses or specific construction worker scenarios, among many others) also may be identified and warrant site-specific screening levels.

For indoor air and other media, alternate screening levels could be developed for site-specific exposure scenarios (e.g., parking garage, construction workers or other receptors) using site-specific exposure parameters or using alternate target risk levels. Because these scenarios are unique and there are multiple methods to develop screening levels (CCME 2010), it is recommended that the approach be discussed with the regulatory agency prior to development of site-specific screening levels.

Screening levels can be developed using site-specific exposure information for the alternate receptor scenarios. The exposure assumptions for developing air, soil vapor, and groundwater screening levels typically include the following:

ET = exposure time (hours/day)
EF = exposure frequency (days/year)
ED = exposure duration (years)

For a site-specific screening level, exposure time could be modified to any period of time of a day to account for site-specific conditions (e.g., operating hours) or the specific hours that a receptor might be present at the site. Similar considerations are applicable to the other exposure parameters of exposure frequency and exposure duration. The exposure parameters may be site-specific, but they should also generally be identified using the same approach as the parameters for default screening levels, which is by determining the reasonable maximum exposure (RME) value for the given parameter for a given receptor. RME is discussed in **Section 8.6** as an element of site-specific risk assessment. The site-specific receptor scenario and associated exposure parameters can then be incorporated into the calculation of the site-specific screening levels. The equations for calculating screening levels are discussed in the **Screening Levels Fact Sheet**.

The degree to which receptors and exposure parameters can be adjusted is highly state- and site-specific. Consult with the appropriate regulatory authority before applying these adjustments.

8.5.2. Background Concentrations

The development of background air concentrations is discussed in detail in the **Background Sources to Indoor Air Fact Sheet**. This section specifically considers how background air concentrations can potentially be incorporated into the development of site-specific screening levels.

Generally speaking, indoor air is a mix of outdoor air, potential subsurface vapors, and/or vapors from items within the building, with outdoor air making up the vast majority of indoor air. Concentrations of VFCs in indoor or outdoor air unrelated to a release from a site are considered background. Other contributions to indoor air may be attributable to multiple sources (e.g., household or commercial/industrial activities, consumer products, building materials). Contributing sources unrelated to site contamination can be highly variable, but certain analytes have background detection frequencies in indoor air that are greater than 90%, even absent a complete VI pathway (e.g., BTEX, acetone, certain freons, carbon tetrachloride; Dawson and McAlary 2009; Plantz et al. 2025; Rago et al. 2021; USEPA 2011a). The background concentrations of chemicals present in indoor air can be above generic indoor air screening levels for certain VFCs (e.g., benzene, carbon tetrachloride, chloroform, naphthalene, 1,2-dichloroethane). As such, these background contributions could be identified as exceeding health-based

target concentrations based on applicable cancer and/or non-cancer risk thresholds but are unrelated to VI. If the chemicals are present due to background sources, then typically no further action would be warranted for VI.

Background concentrations can be an important consideration because of the potential for background sources to result in concentrations that are above the default screening levels. To consider background in the application of site-specific screening levels, MLEs are used to support a conclusion as to whether the presence of one or more of the chemicals is due to sources other than VI. The more evidence gathered to support such a conclusion, the stronger the justification for the resulting decision. Site-specific decisions should be made as to the number and types of information employed.

Strategies for assessing the influence of background sources on indoor air concentrations can be implemented prior to, concurrent with, or after a VI investigation (USDOD 2017). Field methods to determine background contributions to indoor air concentrations can be employed during an investigation or as a stand-alone evaluation as discussed in **Chapter 7: Sampling and Analysis** of this guidance document. Other methods for determining background (that do not require going into the field) often use data from previous investigations or studies or regulatory databases. Many of these methods may be employed at any point of an investigation depending on whether the objective is to understand historical data when planning an investigation or to evaluate suspected background impacts when VI sources were not positively identified. Each of these evaluations may provide MLE that need to be supported to conclude VFCs are from a background source. Additional discussion of background and MLE is presented in the **Background Sources to Indoor Air Fact Sheet** and **Multiple Lines of Evidence Fact Sheet**.

If a chemical is determined to be present due to sources other than VI, the second part of the evaluation that is important for developing site-specific screening levels is determining what the typical concentration of the chemical is in indoor air. Once the background level is established and a representative concentration is determined in accordance with relevant state guidance, the background concentration can be used as a site-specific screening level, as an alternative to the generic value. Background concentrations would typically only be applied as site-specific screening levels in cases where the background concentration exceeds a generic non-cancer and/or cancer risk–based screening level. It should be noted that site-specific screening levels based on background should not be used in a screening risk assessment to calculate risk, as they are not risk-based screening levels. If a site-specific screening level based on background is incorporated into a risk assessment and the concentration in indoor air is below the site-specific screening level, then the VFC would be excluded from further consideration in the risk assessment. It is recommended that the approach for incorporating background levels when developing site-specific screening levels is discussed with the regulatory agency prior to implementing such an approach. In addition, it can often be important to effectively communicate with the public and other stakeholders about the process for identifying background levels and deciding what chemicals are present due to background levels, in order to address potential concerns that may arise if a decision is made not to address certain chemicals.

8.5.3. Attenuation Factors

AFs as a general topic are discussed in detail in the **Attenuation Factors Fact Sheet**. This section specifically considers how site-specific AFs can be incorporated into the development of site-specific screening levels, typically for soil vapor or groundwater, including how an AF can be derived and then applied for decision-making.

The AF usually represents the ratio of the target indoor air concentration within a building to the vapor-phase or groundwater concentration in subsurface media underlying or adjacent to a building. AFs are used by a number of agencies to calculate media-specific screening levels or predict indoor air concentrations. These AFs can be derived either empirically or through the use of VI models.

Typically, development of a site-specific screening level begins with a target concentration in indoor air and a site-specific AF related to the media of interest. Site-specific AFs can be developed to relate the target indoor air concentration to a derived subsurface screening-level concentration (i.e., for sub-slab, soil vapor, and/or groundwater). The screening level for the medium of interest is calculated as a ratio of the target indoor air concentration and the site-specific AF, as follows:

Sub-slab or soil vapor:

$$SL_{site-specific} = \frac{SL_{IA}}{AF_{site-specific}}$$

Groundwater:

$$SL_{site-specific} = \frac{SL_{IA}}{H' AF_{site-specific}}$$

Empirical site-specific AFs may be calculated by relating a measured indoor air concentration to either a subsurface soil vapor concentration (AF_{sv}) or groundwater concentration (AF_{gw}) as follows:

$$AF_{sv} = {C_{indoor}}/{C_{soil\ vapor}}$$

and

$$AF_{gw} = {C_{indoor}}/{\left(C_{groundwater} \times H' \times 1{,}000\ (\frac{L}{m^3})\right)}$$

where H' is the chemical's dimensionless Henry's Law constant.

As shown in these equations, the key inputs for determining site-specific AFs are the concentrations in indoor air and the concentrations in the medium of interest used as the basis for calculating the AF. It is also important when calculating a site-specific AF using site data to be aware that data are needed both for indoor air and another medium. To calculate a robust site-specific AF, sufficient data are needed to characterize concentrations in both of these media. In addition, AFs are typically chemical-specific, so the data used in the calculation of the AF should represent the data for the same chemical for indoor air and the other medium. AFs for different VFCs at a site should be similar, and if a significant difference in the site-specific empirical AFs for different VFCs is observed, the CSM and potential influence of background sources should be reviewed to support the site-specific AF.

There are many potential approaches to both determining the indoor air, soil vapor, and/or groundwater concentrations and identifying a final site-specific AF (e.g., (Abbasi et al. 2023; California DTSC 2021; Lahvis and Ettinger 2021; USEPA 2012b). Some potential considerations or approaches are listed below; however, the list is not necessarily exhaustive:

- Chemical considerations:
  - What chemical(s) should be used to calculate site-specific AFs? Some considerations for identifying the VFC(s) are listed below:
    - What are the main COCs for the site based on the CSM?
    - What are the detection frequencies of VFCs in indoor air and the medium of interest?
    - For indoor air, consider whether background sources may be present and whether the AF calculation should include only indoor air detections above background.

- Source strength:
  - Consider the concentrations in soil vapor and indoor air relative to whether they are indicative of potential VI.
  - For soil vapor and groundwater, consider whether a lower-bound concentration should be identified, such that low concentrations would be excluded from the determination of site-specific AFs because the concentrations in the media would be unlikely to lead to concentrations in indoor air that would be a VI concern.
- Spatial and temporal considerations:
  - Sub-slab soil vapor and soil vapor:
    - Calculate AFs for each paired indoor air/sub-slab sample result (if there are pairs).
    - Calculate AFs for each paired location using data from multiple sampling events.
    - Calculate AFs by building; if sufficient samples are collected, using an upper percentile value such as the 95th percentile should be considered for calculating AF.
  - Ideally, data should be available for sampling events across multiple seasons to capture potential seasonal variability in concentrations and degree of attenuation
- Data considerations:
  - How are nondetect results incorporated into the AFs? For indoor air, one option is to use the reporting limit as the concentration in the AF calculation. Another is to only use paired samples where both results are detected. For media other than indoor air, nondetect results would not typically be used in an AF calculation. Consult with the appropriate regulatory agency for recommendations on handling nondetects in an AF calculation.
  - What are the building operating conditions? If building conditions vary over sampling events, this may need to be considered in the identification of the data sets for calculating the site-specific AF. For example, was the HVAC system operating during all sampling events?

Once the site-specific AFs are calculated, they can be applied to the calculation of site-specific screening levels. Depending on the site, AFs may be calculated and applied to site-specific screening levels for specific buildings, specific site uses (e.g., commercial or residential), or site wide. As mentioned previously, AFs are media specific, so the resulting site-specific screening levels are also media specific. If multiple AFs are calculated and there are a sufficient number for statistical analysis, a cumulative site-specific AF may be calculated as an upper-bound percentile (e.g., 80th percentile or 95th percentile) of the pool of calculated site-specific AFs. Either a maximum or an upper-bound percentile value would generally be considered to conservatively represent potential VI conditions at the site. (Note that for AFs, an upper-bound percentile is conservative because it represents a higher potential for VI, since the AF is inversely related to the site-specific screening level. Therefore, an AF of 0.001 would result in a site-specific screening level 10 times lower than if an AF of 0.0001 was used.) Other techniques to calculate AFs that may be particularly relevant for empirical AFs based on low source strength data sets may also be used (McHugh et al. 2004; USEPA 2012b).

Discussing the use of site-specific AFs in the development of site-specific screening levels with the regulatory agency is recommended prior to implementing such an approach.

8.5.4. Modeling

Models may also be used to evaluate site-specific AFs. AFs calculated by modeling can capture site-specific details including sample depth, soil characteristics, building ventilation, and vadose-zone biodegradation.

If any of the data collected during the VI investigation indicate that concentrations are greater than default (regulatory) screening levels, predictive modeling also may be used to assess whether the subsurface media concentrations are high enough to potentially migrate into overlying buildings. Groundwater, soil vapor, and sub-slab data can be used to estimate indoor air concentrations in buildings using VI contaminant transport modeling.

Details on the purpose, use, and limitations of models are discussed in **Chapter 9: Modeling**.

8.5.5. Special Scenarios

Similar to VI into buildings, vapors from the subsurface may also migrate to excavations and trenches from the subsurface or from water containing VFCs pooling in the base of the excavation or trench. At least one agency has developed soil vapor and groundwater screening levels for a construction or utility worker in an excavation or utility trench (VADEQ 2024). Though not VI, soil vapor screening levels may be used in some cases to screen subsurface soil vapor data for a dry trench scenario. For scenarios where a trench or excavation intersects the water table, screening levels include dermal and incidental ingestion components and inhalation of vapors volatilizing directly from the ponded water in the base of the excavation. Screening levels for scenarios in which groundwater does not enter the trench but vapors migrate through the base or sides of the excavation from groundwater present beneath the trench are also available. Some regulatory agencies have not derived screening levels for this exposure scenario but rather request that the regulatory agency be contacted to discuss the technical evaluation approach (Montana DEQ 2021).

Another scenario is water intrusion into a building, followed by direct volatilization inside the building. This is discussed further in the **Direct Volatilization to Indoor Air Fact Sheet**.

8.6. Site-Specific Risk Assessment

This section describes how site-specific risk assessments are conducted and used. See ITRC RISK-3 (2015) for details on the risk assessment process.

In addition to comparing site data to default or site-specific screening levels or conducting a screening risk assessment, a site-specific risk assessment can be prepared. Similar to site-specific screening levels, a site-specific risk assessment offers more flexibility than a screening risk assessment and the opportunity to use parameters that are specific to the site, rather than the default assumptions inherent in default/generic scenarios. Some regulatory programs require a risk assessment as part of the site investigation process because risk assessment provides more context to the data, which can be interpreted to determine the applicable next steps at a site (e.g., no further action, remediation/mitigation).

This approach provides the following benefits:

- Is a more flexible risk assessment approach.
- Can be modified to evaluate site-specific exposure scenarios, receptors, and other specific situations, which can address the likely exposure scenarios that exist at a site.
- Provides a more realistic estimate of risk based on actual site activities and uses.

This approach has the following applications:

- Consider VI risk cumulatively with risk from other exposure pathways
- Requirement for a regulatory program to conduct a site-specific risk assessment

Site-specific risk assessments typically follow four standard steps: hazard identification, exposure assessment, toxicity assessment, and risk characterization, which includes uncertainty assessment. This section discusses the process for performing a risk assessment for potential VI. For simplicity, the discussion in this section assumes that VI is the only exposure pathway, but if this is not the case, the VI health risks must be considered cumulatively with health risks from other exposures. The risk assessment framework that is presented herein is generally consistent with risk assessment approaches as identified by USEPA's *Risk Assessment Guidance for Superfund, Part A* (USEPA 1989) and USEPA's *Supplemental Guidance for Inhalation Risk Assessment Part F* (USEPA 2009). If a risk assessment is being conducted under a state program, the applicable VI or risk assessment guidance should be consulted.

The following subsections discuss how to conduct a site-specific risk assessment and how to interpret the results of the evaluation. For a more comprehensive understanding of risk assessment, see ITRC's RISK-3 guidance (2015).

8.6.1. Hazard Identification

8.6.1.1. Overview

As with the other data evaluation approaches, a data quality review should be completed as an initial step. With respect to site-specific risk assessment, consistent with USEPA's *Risk Assessment Guidance for Superfund, Part A* (USEPA 1989), data evaluation for risk assessment should include the following steps:

- Gather all available data from the site investigation.
- Evaluate data quality and adequacy (see **Section 8.2.1** and **Data Quality and Adequacy Fact Sheet**).
- Use screening levels or other selection criteria to screen the VFCs to be evaluated (i.e., selection of COPCs).
- Compare potential site-related contamination with background (see **Background Sources to Indoor Air Fact Sheet**).
- Finalize the data set for use in the risk assessment.

For the purposes of this section, it is assumed that adequate data of sufficient quality are available to conduct a site-specific risk assessment. In addition, establishing and evaluating background concentrations is discussed in detail in the **Background Sources to Indoor Air Fact Sheet** and briefly above in the site-specific screening levels in **Section 8.5.2**. The concept of background in risk assessment is that background does not contribute to risk as it is an exposure that would occur regardless of the presence or absence of the subject site. Therefore, chemicals present due to background may be excluded from VI risk assessment as allowed by the state or federal oversight agency.

Selection of COPCs is discussed as part of the screening risk assessment (**Section 8.4**). The concept of and options for COPC screening is similar for site-specific risk assessment. One option, which is most conservative, is to include all VFCs detected in the medium regardless of provenance. This would not include consideration of chemicals as present due to potential background or indoor sources.

Chemicals can also be screened as COPCs using the lower of the non-cancer and cancer-based screening levels. Then, if the maximum detected concentration of a chemical is below that screening level, depending on the regulatory guidance or requirements, this chemical may be screened out of the risk assessment and not further evaluated. MLE are available for evaluating VFCs as COPC in risk assessment (see the **Multiple Lines of Evidence Fact Sheet** for the evaluation approach).

8.6.1.2. Exposure Assessment

Exposure assessment includes the identification of relevant receptors (people who may be exposed to chemicals in air), pathways, and exposure points; the calculation of exposure point concentrations; and the exposure calculations. For a given site, sources, pathways, and receptors are identified as part of the development of a CSM (see **Chapter 4: Conceptual Site Model**). Consistent with the rest of this chapter, the only exposure pathway considered herein is inhalation of air as the pathway relevant to VI.

Typical receptors addressed by default screening levels include adults and children exposed in a residential setting and adults exposed in an occupational environment. In contrast to a screening risk assessment, for a site-specific risk assessment, other site-specific exposure scenarios (e.g., schools, day-care facilities, recreational facilities, or specific construction worker scenarios) may also be evaluated as needed on a site-specific basis.

For each receptor, exposure parameters such as exposure frequency, exposure duration, and exposure time are used to evaluate exposure. In a site-specific risk assessment, site-specific parameters can be identified and used in place of default parameters, as applicable. Site-specific values can be used for one or more of the exposure parameters and may be equal to, higher than, or lower than default values. For example, in most cases, the default exposure assumed for a commercial worker would be an exposure time of eight hours per day, 250 days per year, for 25 years. If it is known that a particular space or building is not intended or designed for full-time occupancy (eight hours per day), the exposure time could be changed to reflect building or site-specific conditions.

Crucially, whenever site-specific exposure parameters are contemplated, it must be kept in mind that a risk evaluation is typically intended to reflect an RME for a given receptor, which is defined by USEPA as the highest exposure that could reasonably be expected to occur for a given exposure pathway at a site. RME is intended to account for variability in exposure parameters such that the parameters selected are representative of most of the receptors in that group and provide a conservative estimate of exposure (USEPA 1992). Use of alternative site-specific exposure parameters must be documented and supported in the documentation provided for the site-specific risk evaluation.

The next step in the process is exposure points. As discussed in the Screening Risk Assessment in **Section 8.4**, there are many possibilities for identifying exposure points in a risk assessment. For a site-specific risk assessment, exposure points are identified on a site-specific basis. Depending on the site, exposure points could be identified as each individual sampling location, by general usage patterns of the spaces, or by building, for example.

If there are multiple indoor air sampling locations within, for example, one specific residence or one commercial building, it may be feasible to consolidate the data to represent a single exposure point, depending on how the locations are used (e.g., if a sampling location is a specific office, that may be reasonable as a separate exposure point; if there are multiple sampling locations within a larger commercial space, then there could be a potential justification for collectively evaluating these as one exposure point). For soil vapor, the considerations are similar—soil vapor can be evaluated on a point-by-point basis (this could be a useful approach for vacant sites, for example, where future buildings are unknown), or using some spatial combination of soil vapor locations. For example, soil vapor locations within or around a specific building could be combined as an exposure point.

For each exposure point, a concentration is needed to represent the exposure point concentration for the specific receptor. Environmental sampling of indoor air or other media represents a snapshot in time and space and may not represent the entire distribution of concentrations over time. To account for this uncertainty, a maximum detected concentration for each COPC for each exposure point can be used as an exposure point concentration. In this respect, even if multiple sampling locations are combined into an exposure point, the exposure point concentration would represent a worst-case exposure as it assumes a

person is exposed to the maximum concentrations of the COPCs for the sampling points for the entirety of the exposure duration.

With sufficient data, alternative exposure concentrations in air could be developed with less uncertainty, which can also account for both temporal and spatial considerations. This applies both to air and soil vapor data, where adequate data for risk evaluation would most often consist both of multiple sampling locations and also multiple rounds of sampling. For soil vapor, only data for sample locations specific/relevant to the building and potential vapor migration should be used for assessing risk for building occupants.

Spatially, as discussed under exposure points, concentrations could be combined across sampling locations. In addition, if data are available from multiple sampling events over time, those data could also be combined. With a combined data set, the most common approach to determine an exposure point concentration would be to calculate a 95UCL, which would provide a conservative upper-bound estimate of an average concentration in that medium. 95UCLs can be calculated using software such as USEPA's ProUCL (USEPA 2022). The selection of exposure point concentrations should be discussed in the uncertainty section to provide an assessment of the selection of exposure point concentrations on the findings of the risk evaluation. Spatial and temporal differences in concentrations for sample data subsequently combined to estimate exposure and the relative effect on risk estimates should be discussed. Also, it may be advisable to consult with the applicable regulatory agency to gain concurrence on an approach for calculating EPCs, particularly when combining data across space and/or time.

After the receptors, exposure points, and EPCs are identified, exposure can be calculated. To quantify inhalation exposures, standard risk assessment equations are identified in USEPA guidance (2009), as shown in **Table 8-2**. Typical default assumptions are identified in various USEPA and state risk assessment guidance (California DTSC 2019; MassDEP 2016; NJDEP 2021; USEPA 2009). Site-specific assumptions (as discussed above) can be used in these equations to assess site-specific exposures for unique receptors.

Table 8-2. Equations to calculate inhalation exposure.

Endpoint	Exposure Equation
Average daily exposure, noncarcinogenic (hazard quotient); units are µg/m^3	$\frac{\mathrm{Ca} \times ET \times EF \times ED \times CF}{ATnc}$
Lifetime average daily exposure, carcinogenic (incremental risk); units are µg/m^3	$\frac{\mathrm{Ca} \times ET \times EF \times ED \times CF}{ATca}$

Where:

Ca = exposure point concentration in air (typically µg/m^3, see **Units and Unit Conversions Fact Sheet** for information about units)
ATnc = averaging time for noncarcinogens (days, as equivalent to ED)
ATca = averaging time for carcinogens (days)
ET = exposure time (hours/day)
EF = exposure frequency (days/year)
ED = exposure duration (years)
CF = day/hours conversion factor (0.042)

If evaluating soil vapor data in a site-specific risk evaluation, indoor air concentrations needed to calculate exposure are estimated from the soil vapor concentrations using an appropriate AF. The soil

vapor concentration used in this equation should be the soil vapor EPC, calculated as discussed above. Indoor air EPCs can be estimated from the soil vapor EPCs using the following formula:

$$C_{IA} = C_{SV} \times AF$$

Where:

C_{IA} = exposure point concentration for indoor air
C_{SV} = exposure point concentration for soil vapor
AF = attenuation factor (unitless)

This relationship depends on the indoor air and soil vapor concentrations having the same units, such as µg/m^3 or ppbv. As long as the concentrations are in the same units, these equations can be applied. For further discussion of units, please see the **Units and Unit Conversions Fact Sheet**.

8.6.2. Toxicity Assessment

The toxicity assessment describes the relationship between the level of exposure and the likelihood and/or severity of an adverse effect and is usually defined using information obtained from published literature describing epidemiologic or toxicological studies. The specific inputs identified as part of toxicity assessment are the toxicity values used to predict the likelihood of adverse health effects in identified receptors at site-specific exposure levels.

The toxicity values used in a site-specific risk evaluation address two categories: (1) toxicity data associated with threshold (noncarcinogenic) effects and (2) toxicity data concerning carcinogenicity. The use of toxicity values as described herein is consistent with the approach used by the USEPA (2009).

Noncarcinogenic effects for the inhalation exposure route are evaluated by a reference concentration (RfC) (USEPA 1994). RfCs provide a benchmark for the daily dose to which humans may be subjected without an appreciable risk of deleterious effects during an average 70-year lifetime. RfCs for inhalation exposure are usually presented in units of milligrams of contaminant per cubic meter of air (mg/m^3).

Cancer risks for the inhalation exposure route are evaluated using an inhalation unit risk (IUR). The IUR is the 95UCL of the mean incremental lifetime cancer risk (ILCR) estimated to result from lifetime exposure to an agent if it is in the air at a concentration of 1 ug/m^3. The IUR is in units of risk per µg/m^3.

Toxicity values (RfCs and/or IURs) are published by USEPA in the Integrated Risk Information System (IRIS) database (USEPA ORD 2025) as Provisional Peer Reviewed Toxicity Values (PPRTVs), as provided on the Oak Ridge National Laboratory (ORNL) PPRTV website and in other sources, including the USEPA Health Effects Assessment Summary Tables (USEPA 1997) and the Agency for Toxic Substance Disease Registry (ATSDR 2024a). Other agencies such as the California Office of Environmental Health Hazard Assessment and the Texas Commission on Environmental Quality have developed their own toxicity criteria for inhalation exposures independent of the USEPA.

Toxicity information is not always available for all chemicals that allows for risk or HI to be calculated. In some cases, toxicity values for surrogate chemicals can be identified based on similar chemical structures. If no relevant toxicity information is available, risk calculations are generally not performed, and these chemicals should be addressed in the uncertainty section of the risk evaluation. When no toxicity values are available, another option may be to consult with the applicable regulatory agency to determine whether any alternative approaches could be used.

8.6.3. Risk Characterization

The following calculations are used to combine exposure calculations with toxicity criteria to produce a quantitative estimate of risk (Table 8-3).

Table 8-3. Equations to calculate potential inhalation risks and hazards that include exposure and toxicity.

Endpoint	Calculate Potential Health Risk or Hazard	Calculate Target Air Concentration
Noncarcinogenic (hazard quotient)	$\frac{\text{ADE}}{RfC}$	$\frac{\text{THQ} \times RfC}{\text{ADE}}$
Carcinogenic (incremental lifetime cancer risk)	$\text{LADE} \times IUR$	$\frac{\text{TR}}{IUR \times \text{LADE}}$

Where:

ADE = average daily exposure
LADE = lifetime average daily exposure
IUR = inhalation unit risk value ($[\mu g/m^3]^{-1}$)
RfC = reference concentration ($\mu g/m^3$)
THQ = target hazard quotient (unitless)
TR = target risk (unitless)

The other variables in these equations were previously defined. Note that the units for ADE **must** match the units for the RfC, and the units for the LADE **must** match the reciprocal units for the IUR.

Cumulative cancer risk and the non-cancer HI are calculated by summing the cancer risks and HQs for all VFCs evaluated, respectively.

Cancer risk is generally described as an ILCR, which is a sum of the predicted cancer risk for all the COPCs (VFCs). Cumulative ILCRs between 1×10^{-6} and 1×10^{-4} correspond to theoretical probabilities of one chance in one million to one chance in 10 thousand excess lifetime cancer risk. There is some variability in acceptable cumulative and/or target ILCRs established by various regulatory agencies with most within the range of 1×10^{-6} to 1×10^{-4}.

Noncancer effects are described as an HQ for a single chemical or total HI, which is the sum of HQs for chemicals contributing to the same adverse health effect. A total HI of less than 1 indicates that it is unlikely that adverse human health effects will occur during a lifetime in an exposed population, including sensitive subpopulations (USEPA 1989). There are certain instances or certain states where an HI other than 1 may be used in specific contexts or types of risk evaluations.

8.6.4. Uncertainty Analysis

Uncertainties and bias are inherent in the risk assessment process. Uncertainty in the results of a risk assessment refers to a lack of knowledge of how well the calculated risk results represent the actual risks. When only a single risk value is presented for any chemical and exposure pathway, uncertainty may also refer to the unknown amount of variability among possible risk assessment results. Available data quality, incomplete information about existing conditions and future circumstances, and other factors

contribute to these uncertainties. The uncertainty can lead to an over- or underestimation of potential risk.

A common approach for addressing uncertainty in a risk evaluation is to apply conservative assumptions to help ensure that risk estimates are protective of most potential receptors. This approach introduces a protective bias in an attempt to ensure that risks are not underestimated. This protective bias is reflected in the methods for developing chemical-specific toxicity criteria (Section 8.6.2) and in the emphasis on identifying RME (Section 8.6.1.1) in the exposure assessment.

Risk assessment results should present an accompanying evaluation of the key uncertainties and biases specific to the chemicals and exposure pathways at a particular site to be of use in supporting risk management decisions. For example, this could include a sensitivity analysis of the factors used in the risk assessment to show how the various assumptions used affect the outcome of the risk evaluation.

8.6.5. Interpretation and Multiple Lines of Evidence

Comparing the ILCR and HI to the risk thresholds will provide an indication of whether mitigation and/or remediation may be warranted. Additional interpretation of the risk evaluation may also be advisable to better understand the results. For example, some questions that could be asked may include the following:

- What are the VFCs that are contributing the most to the cancer risk and/or HI?
    - This can be determined by looking at chemical-specific risks and hazards and identifying the highest values.
- Do any of the VFCs pose additional concerns due to the nature of toxicity and/or presence of sensitive receptors that may warrant a quicker response action?
- Is the presence of this/these VFC(s) likely attributable to VI?

When volatile chemicals with multiple potential sources are measured in indoor air, it may be necessary to gather MLE to support a remedial decision based on the results of the site-specific risk assessment. The premise is that if it can be demonstrated through MLE that an indoor air concentration above a remediation goal is not derived from a subsurface source, no remediation is warranted because the indoor air concentrations may be due to background source(s). (Such MLE can also be used to support risk communication of these types of decisions; see Chapter 3: Community Engagement for additional discussion.) The more evidence gathered to support such a conclusion, the stronger the justification for the resulting decision. Site-specific decisions should be made as to the number and types of information employed. The use of MLE may not be required if only a few or even one provide clear evidence of either background or VI sources. See the Multiple Lines of Evidence Fact Sheet for additional discussion.

8.7. Cleanup Levels

This section describes approaches to developing cleanup levels. Screening levels (discussed above) are typically used to evaluate results of site investigations in order to make site management decisions (Is additional investigation needed? Is mitigation needed?). Cleanup levels are different and focus on the mitigation objectives.

As described in USEPA guidance (e.g., USEPA 1989), COPCs may become COCs based on the results of the risk evaluation (i.e., any of the methods described in Section 8.3 through 8.6). The USEPA framework also describes preliminary remediation goals (PRGs) or cleanup levels. Briefly, site-related COPCs that meet certain risk thresholds would typically be identified as COCs, and then PRGs would be developed for those COCs. Depending on the PRGs, a remedial approach will be developed. PRGs can be based on

default exposure scenarios (as evaluated in a screening risk evaluation) but more often will incorporate the site-specific assumptions incorporated in a site-specific risk assessment. In addition, cleanup levels can be identified based on different risk targets (e.g., ILCR of 1×10^{-6}, 1×10^{-5}, or 1×10^{-4}).

If some form of remedy is required, cleanup levels should be determined based on site-specific conditions and not necessarily default to regulatory screening levels, unless a default scenario is applicable. Cleanup levels should be based on site-specific exposure and follow the process outlined in the NCP (USEPA 1990) or relevant state guidance. In some cases, cleanup levels can be derived using models provided the site is adequately characterized and the CSM is complete. For VI, cleanup levels may be necessary for multiple media, including potentially air, soil vapor, groundwater, and soil. The factors discussed in **Sections 8.5** and **8.6** that are applicable to developing site-specific screening levels and conducting site-specific risk assessments are also generally applicable to determining site-specific cleanup levels.

This portion of the page left blank intentionally. Next chapter begins on the following page.

CHAPTER 9: MODELING

9.1. Purpose and Limitations

The primary purpose of most VI modeling is to estimate average indoor air concentrations of VFCs from known data such as VFC concentrations in soil vapor or groundwater, depth to source, soil type, and other environmental and building parameters (e.g., dynamic controlling factors). Modeling can be used to develop AFs, assess human health risk, and set cleanup goals for VFCs. When practical, modeling should not be used in lieu of collecting indoor air samples; however, there may be scenarios where modeling can be used as a screening tool (please see **Chapter 5: Site Screening** for more information on site screening) or as an LOE to support VI evaluation and decision-making. **Section 9.2** is an overview of the general process for using VI models. **Section 9.3** covers the types of VI models available.

Scenarios for which VI modeling may be a useful tool in supporting VI pathway evaluations include the following:

- When sites without buildings will be developed. Development of a vacant lot or redevelopment of property is proposed above soil or groundwater contamination. Modeling can be used as a screening tool to help determine whether human health risk is unacceptable and/or remediation or mitigation is required prior to development. The allowance of models to be used for this purpose may vary by regulatory authority.
- When property owners above or adjacent to soil or groundwater contamination do not allow access for indoor air sampling or sub-slab vapor sampling.
- When a groundwater plume has not been controlled and may migrate below buildings of interest, but currently there is no known contamination present beneath these buildings.
- When indoor air samples may be compromised due to other VFC sources (non-source interference). In some cases, it might not be possible to eliminate the background sources, so modeling may be used in lieu of indoor air sampling to estimate the contribution from soil or groundwater sources to indoor air concentrations in the buildings. A combination of indoor air sampling and modeling may in some instances provide useful information. For more information, please see the **Background Sources to Indoor Air Fact Sheet**.
- To develop generic lookup table screening tools for common conditions in a region.
- To back-calculate the soil vapor and/or groundwater contaminant concentrations that are predicted to result in a selected target indoor air concentration of that contaminant.

Modeling does have limitations but can be used as an LOE to support decisions regarding further site assessment. The primary limitation is that there is always some uncertainty regarding the true value of the model input parameters. The greater the range of uncertainty, the larger the range of output values. When site-specific input parameters are not known, default values, literature values, or estimates may be used. Some models are highly sensitive to certain parameters, as discussed in the **Model Sensitivity Analysis Fact Sheet**. If parameters of high sensitivity are unknown and cannot be reasonably estimated and the model predictions cannot be verified, the modeler may find that a particular model is not appropriate for the site or scenario in question. Alternatively, more site-specific data may be collected to better refine the model inputs.

The models discussed below are not designed for sites with preferential pathways such as sewer lines or utility trenches, which require further evaluations (please see the **Vapor Intrusion Preferential Pathways Fact Sheet**). The VI models discussed in this section are not applicable for sites with high levels of

methane from biogenic or thermogenic sources, such as pipeline leaks and/or landfills. The models discussed here may not be suitable for sites with methane under high pressure with advective mechanism as the only means of vapor transport.

This chapter includes guidance on the application of VI models and steps to take for selecting and using a model, including a summary of VI model types and a discussion on the differences between PVI and general VI models (Section 9.2). This chapter also includes more detailed information on using specific models, such as the USEPA VISL (Section 9.3.1 and the Vapor Intrusion Screening Levels Calculator Fact Sheet), the J&E model, including the 2024 Draft California DTSC spreadsheet (California DTSC 2024) (Section 9.3.2, and the Johnson and Ettinger Model Fact Sheet), the PVI BioVapor model (Section 9.3.3, and the BioVapor Model Fact Sheet), the PVIScreen model (Section 9.3.4), and lateral vapor migration models (Section 9.3.5).Three appendices provide more technical details and case examples for the BioVapor model (Appendix H) and the J&E model (Appendix I). Appendix G provides brief descriptions and references for additional VI models and summaries the history and evolution of VI modeling.

9.2. Use of Models for Assessing Vapor Intrusion

Mathematical models may be useful for sites that require further assessment based on the initial screening and application of the vertical screening distances described in Chapter 5: Site Screening. The complexity of modeling applications can vary greatly depending on the objectives of the modeling and availability of project-specific information. Figure 9-1 shows the basic process to follow when using modeling to estimate the potential VI risk or indoor air concentrations of VFCs. The process is iterative and may require rerunning the model with revised input parameters based on the results of verifying the model and conducting sensitivity analysis. The following sections describe these steps in more detail.

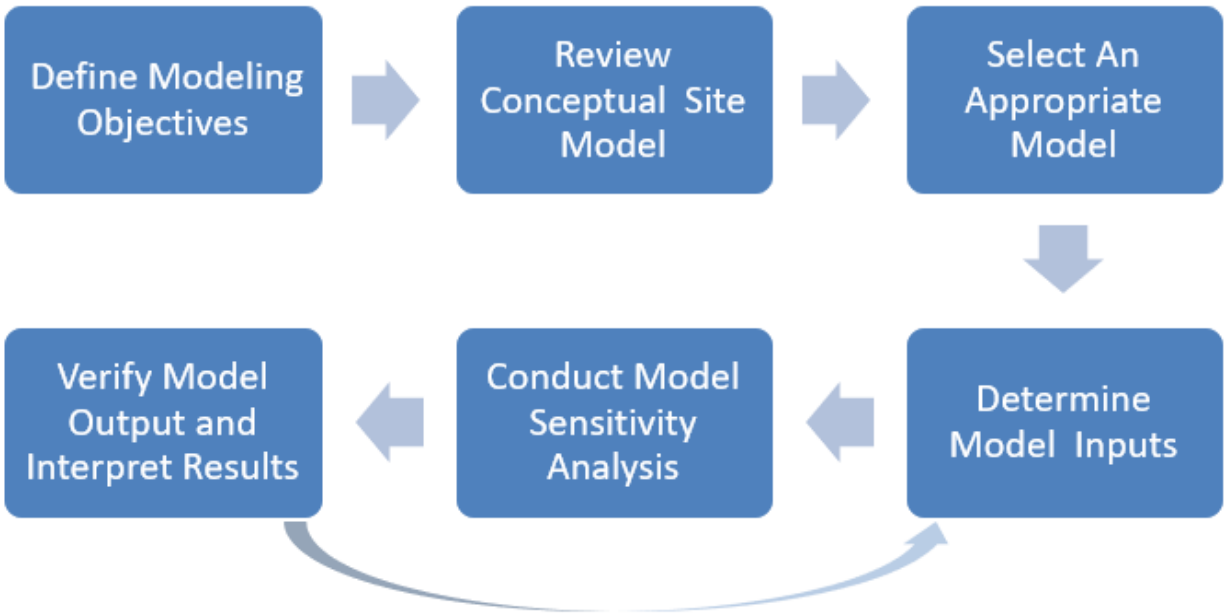


Figure 9-1. Basic steps in the iterative process of using a vapor intrusion model.

9.2.1. Define Modeling Objectives

Prior to conducting any model simulations, the purpose and objectives of the modeling should be clearly understood and defined. The modeling objectives and purpose play a role in model selection. The

objectives can also influence selection of parameter values and can help to determine the level of detail and accuracy required in the model simulations.

The following list includes example applications of VI modeling, along with typical objectives for each modeling application:

- **Support development of screening distances (lateral and vertical):** Modeling studies have an important supporting role in the development of screening distances for PVI (Davis, Patterson, and Trefry 2009; Verginelli and Yao 2021). Models incorporating aerobic biodegradation include use of analytical models (DeVaull 2007; 2011; Verginelli, Yao, Wang, et al. 2016) and numerical models (Abreu and Johnson 2005; 2006; Abreu et al. 2009b; 2009a; USEPA 2012a). An example is included in Figure 9-2 that helps illustrate conditions (distances, source vapor concentrations) for which AFs are smaller than levels of potential concern. Modeling studies support the findings from the empirical studies on screening distances; comparisons of distances between models and data vary depending on the assigned confidence levels for the data sets and the selected model parameters. A key observation is that aerobic biodegradation significantly reduces predicted vapor concentrations and AFs, over short migration distances for commonly observed fate and transport scenarios (i.e., where O_2 concentrations in the shallow subsurface exceed 1%). More recently, modeling was used in the support and expansion of empirical data on vertical attenuation distances of lead scavengers, 1,2-dichloroethane (Kolhatkar et al. 2019) and EDB, also known as 1,2-dibromoethane (Hers et al. 2022).

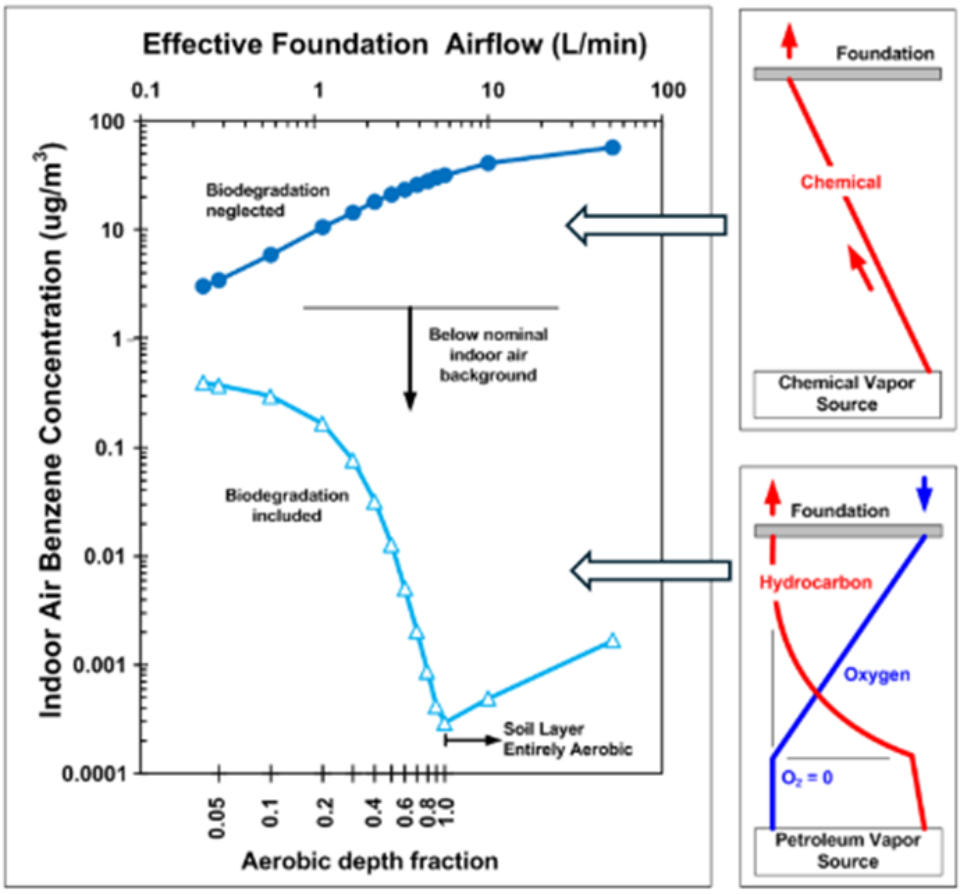


Figure 9-2. Comparison of modeled indoor air concentrations with biodegradation included (light blue) and neglected (dark blue) under conditions of varied foundation airflow. Results are from the BioVapor model. Nominal conditions include a 5-ft (1.5-m) source depth, 1 mg/L benzene, 10 mg/L dissolved total petroleum hydrocarbons, and sandy soil.

- **Support VI investigation and site screening:** Some regulatory agencies use published screening levels based on standard exposure/land use scenarios (i.e., residential and commercial/industrial) and generic default AFs, such as 0.03 for sub-slab vapor and soil vapor and 0.001 for groundwater (USEPA 2012a). When the use of generic default AFs identifies significant efforts for conducting VI investigation (e.g., at multi-building sites and large office complexes/warehouses), modeling can be applied to derive site-specific screening values to allow for prioritization of data collection, (i.e., which buildings or areas of a building should be sampled initially) and when sampling should be performed (e.g., modeling the effect of stack effect and/or HVAC operation).

- **Site-specific predictive modeling to assess current or future site conditions:** Modeling in this context is typically conducted in conjunction with a health-risk assessment. Input parameter values are selected to represent site and building conditions and are most likely conservative to be health protective because of uncertainties and limitations associated with modeling. In some instances, such as where buildings do not currently exist but are planned for the future, modeling can be used to predict vapor migration and attenuation for the future building conditions anticipated at the site. Some agencies have developed restrictive modeling approaches to derive site-specific AFs where model use is constrained or limited, (e.g., relative to increment of change relative to generic factors or based on comparison to empirical data where supported).

- **Site-specific modeling to help develop a CSM:** VI models can be used to help understand key processes and interpret data and to verify the CSM through comparison of model-predicted values to available data. Modeling can also be useful in assessing and explaining key factors affecting VI, and possible future changes in VI, by performing sensitivity/uncertainty analysis. In addition, VI models can be used to identify the possible contribution of background sources to indoor air relative to the contribution from subsurface vapor sources. At petroleum release sites, a biodegradation model, such as BioVapor, may be used to understand measured O_2 and PHC profiles in soil vapor and to evaluate the significance of vapor attenuation processes. USEPA documentation (2012a) presents a comprehensive study that uses models to provide insight on conceptual scenarios including source distribution, contaminant degradation, and soil and building properties.

- **Inverse modeling to develop site-specific cleanup goals:** Models can be used to develop site-specific and depth-specific (for soil vapor) cleanup goals when supported by a robust CSM. Some agencies may allow the derivation of such cleanup goals through inverse modeling. With inverse modeling, acceptable concentrations of contaminants in indoor air are first identified, for example, in the USEPA Regional Screening Levels for ambient air (USEPA 2024a). Then, a site-specific model is used to back-calculate the predicted concentrations needed in soil vapor, soil, or groundwater to attain the acceptable contaminant concentrations in indoor air. This application is especially useful for redevelopment sites (i.e., buildings currently are not present, or the existing buildings will be removed/renovated) and sites where indoor air sampling is not accepted for decision-making. Site-specific cleanup goals or action levels may be used to assess cleanup progress and to evaluate when building mitigation measures, subsurface remediation, and associated monitoring can be terminated. It is good practice to collect indoor air samples post-construction when possible to verify that concentrations are consistent with the model and are protective of human health.

- **Support VI mitigation design:** Although CSMs foundational to the development of a VI mitigation strategy (USEPA 2008), there are fewer examples of mathematical models being used in VI mitigation design. No comprehensive models for simulating VI mitigation components such as barriers and active venting are known to be available; however, there are several examples where specific components of design have been evaluated using models of varying complexity, as follows:

    - A biobarrier, consisting of delivery of atmospheric (ambient) air below and around a building foundation at rates sufficient to maintain aerobic conditions, has been identified as an emerging technology for VI mitigation. An equation to estimate the minimum air injection rate is provided by Luo et al. (2013). This technology is described in the **Aerobic Vapor Mitigation Barrier Technology Information Sheet**.

  - Active VIMS design can include methods to test and mathematically model the sub-slab permeability and transmissivity of sub-slab soil (McAlary, Wertz, et al. 2018; McAlary et al. 2020).

- **Assess building foundation attributes on vapor attenuation:** The BioVapor model can be used to evaluate the relative effect of different factors on vapor concentration attenuation. A modeled example is illustrated in **Figure 9-2** for which reasonable values are assigned for all parameters, then one parameter (foundation airflow) is varied to identify worst-case conditions with biodegradation (i) included and (ii) neglected. The worst-case results differ substantially for the two conditions and can be generalized. For nondegrading chemicals (PCE, TCE), worst-case conditions occur for foundations that pass the most air—that is, a highly permeable foundation such as a dirt floor or a dirt floor in a crawl space. The opposite occurs for aerobically degradable chemicals, including petroleum, for which worst-case conditions occur with a low-permeability foundation that tends to exclude oxygen from below the foundation. This is typically an intact or sealed concrete foundation. To address this, in practice, mitigation, when needed, can include both sealing a floor and adding SSV to provide an alternate pathway for both soil vapor venting and oxygen aeration.

A tiered modeling process is often used to meet the above objectives. Initially, when site-specific data are lacking, a model may rely on generic, conservative assumptions. Predictions at this tier are expected to be conservative and based on a simplified CSM with limited empirical data; thus, the model likely overestimates exposure and health risk. If site management decisions cannot be made at this stage, or the model estimates an unacceptable level of risk at this stage, then the modeling may progress to a refined tier, where some of the conservatism is addressed by using site-specific data and assumptions based on a refined CSM for key model input parameters.

9.2.2. Review Conceptual Site Model

A model application should be consistent with the CSM developed for a site, summarizing the source of vapors, the expected migration pathways, important processes affecting vapor migration and attenuation, and the receptor that may be potentially exposed to the vapors. Clearly document components of the CSM and how they apply to the model. The CSM may contain some uncertainties due to lack of field data. These areas of uncertainty and how they affect the modeling objectives and results should also be documented. As noted in **Chapter 4: Conceptual Site Model**, the CSM should be dynamically refined as site data are collected and compared to model results.

9.2.3. Select an Appropriate Model

An appropriate model should be selected to simulate the physical system defined in the CSM and for which site-specific data are available to populate the model. More complex models demand more input parameters, and the requirements for site-specific data collection increase with model complexity. It is critical that the model formulation and assumptions are consistent with site conditions and the CSM. For example, whether the VI source is or is not beneath the building, and depending on model objectives, selection of a one-dimensional upward transport model may not be appropriate.

Note that state and federal regulatory agencies may require use of specific, publicly available, and/or free models if modeling is being used as an LOE for case decision-making. The use of more complicated or proprietary models, if accepted by the regulatory agency, may require more supporting documentation in a summary report, as described in **Section 9.2.7**. Such models are beyond the scope of this chapter and are not discussed in further detail.

The following models are discussed in greater detail in the sections that follow:

- The USEPA VISL calculator is a simple online tool for estimating health risk based on VFC groundwater or soil vapor concentrations and a nonadjustable defined (empirical) vapor AF.

- The J&E model (Johnson and Ettinger 1991; USEPA 2017a) is a widely used analytical model for estimating indoor air concentrations of VFCs. The J&E model has been widely used for assessing the effects of contaminated vapors on indoor air but is not recommended for evaluation of PVI because it does not include aerobic biodegradation (USEPA 2013c) and is likely overly conservative. Recently, California DTSC released a modified J&E model spreadsheet to address some programming errors identified in the 2017 USEPA version of the J&E model and to allow for use of California-specific toxicity values and building parameters (California DTSC 2024).
- The BioVapor model (API 2012a; 2010), and the USEPA PVIScreen model (Weaver and Davis 2017) are similar in concept to the broadly applied J&E model but, in addition, include aerobic biodegradation.

These models are widely used, readily available, and are plug-and-play type models where spreadsheets and/or fillable forms are used for the inputting of parameters and results are calculated automatically. **Appendix G** has more details on other models that are available through the original papers or provide calculations that the user would need to perform to implement the model.

BioVapor and other models that incorporate biodegradation show distinct behavior for aerobically degradable petroleum vapors. This behavior is illustrated in **Figure 9-3**, which shows the significant effects of biodegradation on benzene, both with increasing vertical building-source separation distance and with lower source vapor concentrations, as compared to results that neglect biodegradation. Modeling of other petroleum chemicals exhibits results similar to **Figure 9-3**, but the precise estimates will vary.

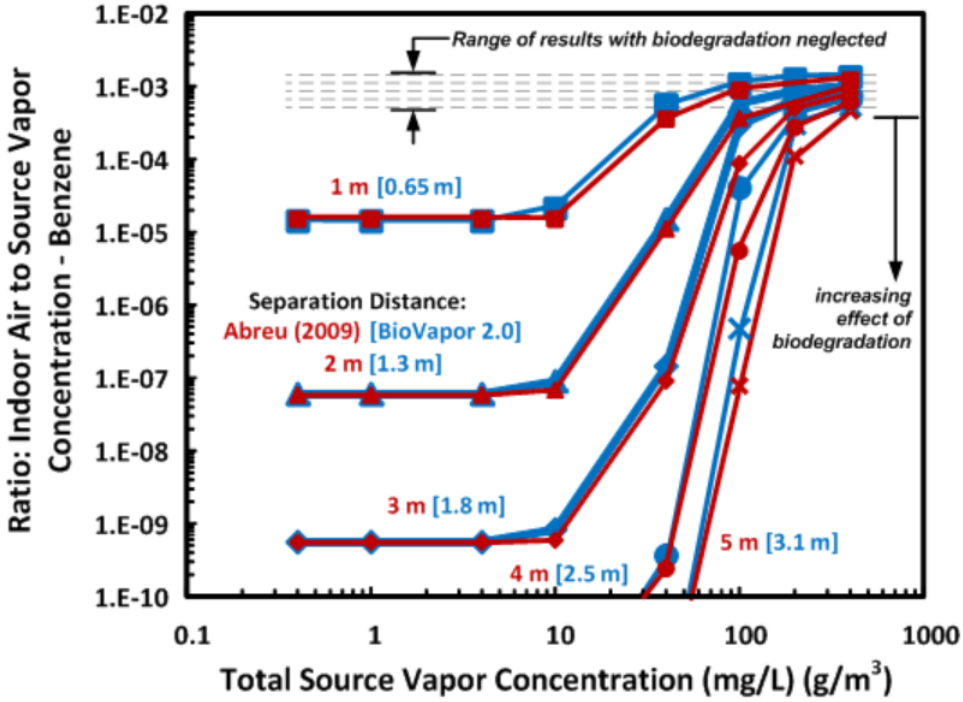


Figure 9-3. Example model results illustrating the effects of biodegradation on chemical concentrations reaching indoor air. Significantly lower indoor air concentrations occur for both lower source vapor concentrations and at increased separation distance, as compared to model results that neglect biodegradation. Both three-dimensional and BioVapor model results are shown in a typical basement scenario for benzene.

Source: Abreu et al. (2009a) and API (2010).

9.2.4. Determine Model Inputs

A tiered process may be applied to modeling by selecting conservative, health-protective values for input parameters initially, followed by site-specific values and assumptions for key model input parameters. When site-specific parameter values are used, they should be technically supported by the site CSM and/or measured data (e.g., soil types/properties).

After selecting the appropriate model to use, begin by populating the model inputs using these steps:

1. Use field-verified values for as many input parameters as possible. For example, depth to VI source and maximum subsurface contaminant concentration should be known for the site prior to modeling. For VFC contamination in groundwater, the depth to groundwater is determined by installing and monitoring one or more groundwater monitoring well(s). Groundwater samples are collected and analyzed for dissolved-phase concentrations of the VFC(s). For soil contamination, or when using a model with the soil vapor input mode, depth-discrete soil vapor samples are collected and analyzed for vapor-phase concentrations of the VFC(s). Generally, these values will remain fixed through sensitivity analysis and model verification.
2. Use the model defaults, if available, for input parameters that do not initially have site-specific values. Note the ranges of possible input values for each parameter, if available in the model guidance manual, as they may be used for the sensitivity analysis later. Most models will begin with default values pre-entered for many of the inputs. These values should be altered only when the model user has more accurate site-specific information or if the default conditions are not consistent with the CSM.
3. Use the model guidance manual and/or literature search to determine the range of applicable values for key input parameters based on the VI CSM for the site.
4. Constrain the ranges of input values for the selected input parameters as much as possible using professional judgment and knowledge of the site conditions. For example, physical soil parameters such as porosity and bulk density may be constrained to narrower ranges when the primary site soil type is known.

Most models will either automatically update the output results once an input value is varied or have a command to rerun the model. If any of the input parameter values fall outside of the applicable range for the model, an error message typically appears, and further input revision is necessary for outputting the results. If no errors are encountered, the model should output results such as an indoor air concentration of a VFC, or a calculated risk number (typically an HQ or cancer risk). When using a model to calculate a risk value, it should be noted that the risk is an incremental increased risk due to VI from the VFC(s) of concern at the site and does not account for unrelated site hazards. Some regulatory authorities may allow a calculated indoor air concentration to be compared to a published threshold value. Further action would be required if the predicted concentration exceeds the threshold value. When using a model to predict risk, the user should be advised to evaluate whether the inputs (e.g., toxicological and/or physical-chemical) are regularly updated. For example, the USEPA publishes screening thresholds of indoor air concentrations for many VFCs online in the Regional Screening Levels lookup tables and calculator. These thresholds correspond to fixed target risks, such as an incremental cancer risk of 1×10^{-6} or an HI of 0.1 or 1.0. The toxicity data used for calculating these thresholds is typically updated twice per year.

9.2.5. Conduct Model Sensitivity Analysis

There is always a degree of uncertainty as to the true values to use for some of the model input parameters. This uncertainty can lead to a reluctance to use a model in the VI assessment process. Identifying parameters that are particularly sensitive (i.e., a small change in the input value results in a

relatively large change in output) can help focus data collection on the information that will improve the model use.

For example, Table 2 in the **BioVapor Model Fact Sheet** shows an applicable range of 0.1–0.5 for the soil porosity input parameter. If the model user does not know the true site-specific soil porosity, they may elect to run the model using end or close to end members of the range. Since the sensitivity of the soil porosity value is high, this will result in a large range of possible outputs (predicted indoor air concentrations). The model user may want to collect soil samples from the site, use knowledge of the soil from nearby or regional sites, perform a literature review, or use another technique to narrow the range of likely input soil porosity values, and therefore narrow the range of outputs. For more information, please see the **Model Sensitivity Analysis Fact Sheet**. Note that the PVIScreen model has a built-in Monte-Carlo analysis and presents results in terms of probability, so a one-at-a-time sensitivity analysis approach may not be necessary for using this model.

9.2.6. Verify Model Output and Interpret Results

After running a simulation of the initial model, the model user should compare the predicted concentrations to those of indoor air or sub-slab soil vapor samples collected at the site. If indoor air and/or vertical soil vapor data are unavailable, the modeler should use experience and professional judgment to assess whether the model outputs seem reasonable. If not, the modeler may revisit the input parameters to better identify values with high uncertainty and/or sensitivity. In that way, the modeling process is iterative and may include multiple revisions based on a sensitivity analysis or new site-specific data that become available as a case progresses. If the model results indicate that the target indoor air concentration or risk threshold is exceeded for existing or proposed buildings at a site, further investigation is warranted and indoor air samples should be collected for verification, if possible.

When comparing model inputs and outputs to measured data, the ranges of model parameter values should be consistent with the CSM and based on empirical data. If they differ significantly, the model and the data are reevaluated, and the model inputs may be adjusted as warranted. Note that the influence of background sources and other interference must also be considered when comparing the results and included in the uncertainty analysis. Typically, model comparisons should focus on soil vapor data if indoor air may be affected by background sources.

9.2.7. Present Model Predictions to Stakeholders and Regulatory Authorities

It may be necessary to present the model results to regulatory authorities and/or other stakeholders, particularly if the modeling will be used as an LOE in site decision-making. Each agency may have its own requirements, but generally the results should be submitted in a report that at a minimum has the following components:

- For each input parameter, a description of how the value was chosen:
  - Was the default value used? If so, does it seem reasonable given what is known about the site?
  - If another value was chosen, supporting evidence, such as soil characteristic data, literature values, experience at similar or nearby sites, etc. should be documented.
  - Was the model run with a range of input values for this parameter? If so, was the range constrained further by conducting a sensitivity analysis and/or collecting more data?
- Screen shots documenting the input values used.
- Screen shots of the model outputs.

- A discussion on whether the model was verified using indoor air and/or soil vapor sampling data.
- A discussion on implications. Were health target levels exceeded in the model? If not, were the assumptions reasonable? Were conservative values used for uncertain parameters so that the model is not likely to underpredict indoor air concentrations?
- Recommendations for further assessment and/or mitigation or screening out a site or buildings based on modeling results. Some agencies may require MLE to support this recommendation. In cases where indoor air data cannot be gathered and/or is not available, the use of a model is the only tool available and therefore highly recommended.
- If a model was used that the agency or stakeholders are unfamiliar with, the computer code selected for the modeling application should be well documented and have been tested for the intended use. A brief description of the model code should be provided in a report along with citations for model documentation.

9.3. Review of Vapor Intrusion Models

This section begins with an overview of three main types of VI models, followed by a more in-depth discussion on specific available models (the J&E model [spreadsheet update 2024], the BioVapor model, and the PVIScreen model). Additionally, models with application to lateral vapor assessment are described because of potential limitations associated with common one-dimensional VI models. A detailed evaluation of VI models is provided in **Appendix G**.

Models for assessment of VI can be categorized according to three general types:

- **Empirical models, which use predictions based on observations from other sites:** Empirical models use an appropriate distance or AF derived from a compilation of relevant data to screen a site for VI potential or to estimate an indoor air concentration. **Chapter 5: Site Screening** provides more detail on using screening distances and AFs. Recent advancements in empirical modeling include work by Kram and Solgi (2025) using machine learning to develop building-specific correlations between barometric pressure patterns and exposure concentration measurements during upward flux conditions. The correlations are used to predict past occupant exposure profiles using historical barometric pressure records.
- **Analytical models, which are mathematical equations based on a simplification of site conditions:** Analytical models are generally steady-state one-dimensional solutions to vapor transport or compartmental models with a planar, uniform source at a specified depth below a building. A critical historical milestone in modeling VI was the development of the J&E model (1991), a compartmental model incorporating diffusion and advection. A USEPA-modified spreadsheet version of the model continues to be widely used for regulatory screening and site-specific evaluation purposes.

A primary distinguishing feature of analytical models for VI application is whether they incorporate aerobic biodegradation. A comparison of models for evaluation of VI both for CVOCs and for PHCs is presented in Bekele et al. (2013). The BioVapor model (API 2010; DeVaull 2007) is a modification of the J&E model incorporating O_2-limited biodegradation and includes improvements on earlier models that included biodegradation (Johnson et al. 1998; Spence and Walden 2011a; 2011b). The USEPA PVIScreen model similarly incorporates aerobic biodegradation.

- **Numerical models, which allow for simulation of multidimensional transport and may provide for more realistic representation of site conditions:** Numerical models offer potential advantages for simulation of conditions requiring additional detail, such as heterogeneity, geometric complexity, and temporal variability. Numerical models have typically been applied to obtain a more detailed understanding of causes and effects of vapor transport and attenuation (specific models are

identified in **Appendix G**). Because of their complexity, numerical models require more data and effort (and therefore have increased cost) than analytical models and thus, for practical applications, are rarely used.

Understanding of VI processes and model development have benefited from radon research and intrusion models. The models have spanned empirical studies (Little et al. 1992) to complex 3-D numerical models enabling soil vapor pathways and specific processes (temperature, atmospheric pressure) to be evaluated (e.g., Loureiro et al. 1990; Robinson et al. 1997). A comprehensive overview of radon research including modeling is provide in Nazaroff (1992). A caution when evaluating radon models is that subsurface distribution and degradation of radon and VFCs are often different, which affects model construction.

9.3.1. Vapor Intrusion Screening Levels Calculator

The USEPA provides a simple to use online calculator and user's guide for assessing VI risk given contaminant concentrations in groundwater, soil vapor, or indoor air. The VISL calculator (USEPA 2024b) is linked to the USEPA Regional Screening Level tables and is updated approximately twice per year. The VISL calculations are based on default vapor AFs and do not include site-specific parameters such as depth to the contamination source, soil type, or building foundation characteristics. As such, the VISL Calculator is a conservative tool that can be used to identify and screen out buildings for which VI is not likely to present an unacceptable risk to human health. For more information on the assumptions, requirements, and inputs for using the VISL Calculator, please see the **Vapor Intrusion Screening Levels Calculator Fact Sheet**.

9.3.2. Johnson and Ettinger Model

The J&E model is the most commonly used model for estimating VFC concentrations in indoor air. With input of either soil vapor concentrations or groundwater concentrations and a partitioning model, the model estimates the associated indoor air concentration and incremental risk. Common implementations of the J&E model are the USEPA online version of Excel spreadsheets (the latest Version 6 was released in 2017) (USEPA 2017b). California DTSC in 2024 released a modified J&E model spreadsheet to address some programming errors identified in the 2017 USEPA spreadsheet and to include an option for an alternate capillary fringe model (for groundwater source) and use of California-specific toxicity values and building parameters (California DTSC 2024). The model is most commonly used for sites where no buildings exist and future buildings are proposed. Additionally, sometimes, it is difficult to obtain indoor air data where access is not available. In such cases the J&E model is the only tool available for VI evaluation.

The J&E model is a steady state, deterministic model that has single-point inputs and outputs. It is based on the basic principles of contaminant fate and transport, contaminant partitioning between media, and the physical and chemical properties of the contaminants themselves. The compartmental model combines diffusion in the unsaturated soil zone, diffusion and advection through foundation cracks, and uniform mixing of vapors in the building enclosed space. Diffusion is the only mechanism for vapor transport within the vadose zone. Soil vapor advection is due to the indoor-outdoor building pressure differential.

As soil vapor flux through the foundation increases, the sub-slab concentration decreases, with a corresponding increase in the diffusive gradient for soil vapor moving upward. For shallower vapor sources (or dry soil) near the building foundation, the sub-slab vapor advection through foundation has the dominant influence on VI, while for a deeper source, the soil vapor diffusion typically has the dominant influence.

The J&E model spreadsheet is most suitable for constant, uniform contamination source homogeneous or layered soil properties with uniform building construction features. Conversely, the model is weakest under variable conditions and cannot evaluate significant preferential pathways, wet basements, substantial lateral transport of soil vapor, large buildings with potential localized sources of vapors beneath them, rapidly changing barometric conditions, and shallow fractured-bedrock conditions. Each of these conditions may have the potential to significantly increase or decrease the rate of VI beyond the model's predictions.

With an understanding of the abovementioned limitations and the use of conservative input parameters (see USEPA 2017b and DTSC 2024 for typical parameter ranges and conservative values), the USEPA J&E model can be used as one LOE to support site screening for current and future (e.g., vacant lots or redevelopment) VI risk. The sensitivity of the J&E model outputs to key input parameters is qualitatively described in **Section I.3 of Appendix I**.

The J&E model should be used only when site conditions match the model assumptions using reasonable site-specific or regulator-approved input parameters (USEPA 2017b). Guidance on the selection of J&E model input parameters is also available in Hers et al. (2003), Weaver and Tillman (2005), Johnson (2005), and USEPA (2017b). Analytical models that can simulate the effects of biodegradation and source depletion of contaminants in soils are discussed in the next section. For complex sites, multidimensional numerical models can evaluate spatial and temporal processes in the VI pathway.

For more detailed information on using the J&E model, please see the **Johnson and Ettinger Fact Sheet** or **Appendix I**.

9.3.3. BioVapor Model

The BioVapor model (API 2010; DeVaull 2007) is a one-dimensional model based on a CSM similar to the J&E model, but it includes aerobic biodegradation. The BioVapor model has been reviewed and accepted by USEPA (Weaver 2012) and is the basis for the USEPA PVIScreen model (2016). Currently, BioVapor has been cited by several regulatory agencies and programs (for example USEPA OUST, California, Michigan, Illinois, Washington and Australia). BioVapor evaluates O_2-limited aerobic biodegradation using an analytical solution to calculate the aerobic depth below ground surface. This calculation describes a shallow aerobic layer where first-order biodegradation occurs and a deeper anaerobic layer where biodegradation does not occur. In the absence of biodegradation, the BioVapor model produces equivalent results to the J&E model.

The BioVapor model helps to assess the significance of data for groundwater, soil vapor, and soil when PHC concentrations exceed applicable screening criteria. The BioVapor model should not be used when LNAPL or contaminated groundwater is in contact with a building, or directly entering a building, because the model does not simulate these conditions. The conceptualization for the BioVapor model is based on a constant, uniform contamination source, diffusion-dominated transport in soil, and a single homogeneous soil layer. There are certain conditions outside of this conceptualization where BioVapor should generally not be used such as significant pressure-driven flow (for example, a landfill setting) or transport through preferential pathways (for example, sewers directly connecting an LNAPL source to a building). There may be other conditions where BioVapor may be applied conservatively or to portions of the site, such as heterogeneous soil layers or nonuniform contamination sources. For BioVapor, as for any model, consult the applicable regulatory agencies to determine whether the model results will be accepted.

Model input parameters for BioVapor (and PVIScreen) are conceptually similar to the broadly applied J&E model and share many similar (often identical) defined model parameters. A qualitative description of the sensitivity of BioVapor model to input parameters is provided in Table 2 of the **BioVapor Model Fact Sheet**, while default values and applicable ranges for model input parameters, including the additional

parameters specific to the BioVapor model, are provided in **Appendix H**. Input parameters for the BioVapor model that affect biodegradation aspects of the model are listed below:

- O_2 supply beneath the building
- Chemical parameters and concentrations, including all PHC sources or degradation products with oxidative demand (such as methane)
- Chemical-specific, first-order biodegradation rate constants
- Baseline rate for O_2 respiration in soils
- Minimum O_2 for aerobic respiration
- Distance from bottom of building foundation to contamination source
- Type of building foundation (which affects the O_2-supply boundary condition).

The BioVapor model has three options for identifying the O_2 supply or flux below the building, consisting of (1) a specified air (O_2 mass) flow rate (can be applicable for conventional depressurized building), (2) specified oxygen concentration at surface directly below the building foundation (can be applicable for crawl-space foundation), and (3) fixed aerobic depth below building (can be applicable when soil vapor data are available below building). Additional information on the BioVapor model is in the **BioVapor Model Fact Sheet** and **Appendix H**.

9.3.4. PVIScreen Model

PVIScreen extends the concepts of the BioVapor model and similarly accounts for oxygen-driven biodegradation of multiple constituents of petroleum in the soil above the water table (USEPA 2016; Weaver 2013; Weaver and Davis 2017). The main difference is that PVIScreen automatically conducts a Monte-Carlo uncertainty analysis, which involves repeated runs of the model using a range of typical values of site-specific factors in accordance with input parameter distributions. This type of formulation allows for probabilistic predictions of model outputs, which can be advantageous when detailed analysis of model uncertainty is warranted. The PVIScreen model code was tested against the BioVapor code, and model documentation includes case example sites.

9.3.5. Lateral Vapor Migration Models

The common modeling paradigm is a one-dimensional model for vapor transport that assumes a lateral vapor source that is of the same size or larger than the building footprint. While numerical models have been used to assess lateral vapor migration and show significant attenuation in vapor concentrations and simulated vapor AFs (Abreu et al. 2009a), there are few available practical tools for assessment of lateral vapor migration. Such an evaluation can be important because small, localized vapor sources that are laterally adjacent to the building of interest are not uncommon, and one-dimensional models may be overly conservative. Yao et al. (2017) present a two-dimensional analytical model for heterogeneous soils where lateral migration may be significant.

One possible approach is to adjust the J&E model inputs based on fundamental aspects of the model construction and input parameters. While the J&E conceptual model is often thought of as a vertical one-dimensional model for vapor transport, it includes a building area term (Ab) that is defined as the "cross-sectional area through which vapors pass," which can be approximated by the subsurface area of both the walls and base of the foundation. The soil vapor advection in the model, Q_{soil}, can be estimated from empirical data or models, such as the perimeter crack model referenced in USEPA (2017b), although there is significant uncertainty in Q_{soil} estimates (Hers et al. 2003; Johnson 2005; Tillman and Weaver

2007; USEPA 2017d). Because in the model contaminated vapors are carried via advection (Q_{soil}) into the building, it may be appropriate to scale Q_{soil} to account for a localized vapor source when the building is large (while keeping the building ventilation rate constant). Any adjustments to model inputs should be performed by a knowledgeable modeler and should be supported by site data (CSAP 2024).

A second approach may be to use a two-dimensional analytical model as an approximation for lateral VI. For example, Lowell and Eklund (2004) describe an analytical model for lateral vapor attenuation that is based on two-dimensional diffusive transport. Nomographs allow the vapor attenuation to be estimated for varying lateral and vertical distances to a building. The source assumptions should align with model assumptions, such as a sharp boundary vapor contamination source.

A related approach that may warrant consideration is where instead of adjusting the model or input parameters, the vapor concentrations in the model are adjusted based on a more representative estimate of near-building soil vapor concentrations. This may be an appropriate methodology when there is a localized vapor source and large building. For example, Michigan has developed a big building model where with sufficient soil vapor or sub-slab vapor data, a weighted average estimation method may be used to estimate soil vapor concentrations for comparison to screening values for big buildings. This approach requires sufficient site-specific vapor data for estimation purposes.

This portion of the page left blank intentionally. Next chapter begins on the following page.

CHAPTER 10: VAPOR INTRUSION MITIGATION

The objective of VI mitigation is to prevent and/or reduce the severity of the migration of VFCs into a building from the subsurface, that is, VI. The basis of VI mitigation design uses the results of the site evaluation, risk assessment, and CSM to determine appropriate response actions and, if warranted, develop and design remediation and/or VI mitigation plans. This chapter will focus on the common strategies and technologies that can be implemented when there are known or suspected VI concerns at an existing or future building. Response actions discussed in this chapter include the following, which may be used in combination to address the VI pathway for the building:

- Rapid response actions
- Remediation and ICs
- Active mitigation systems
- Passive mitigation systems

Each of the above VI mitigation approaches are described in greater detail in the accompanying fact sheets: Rapid Response and Ventilation for Vapor Intrusion Fact Sheet, **Vapor Intrusion Remediation and Institutional Controls Fact Sheet**, **Active Vapor Intrusion Mitigation Systems Fact Sheet**, and **Passive Vapor Intrusion Mitigation Systems Fact Sheet**.

Mitigation technologies can be applied for multiple scenarios to mitigate the VI pathway. Understanding how a given mitigation technology is designed to mitigate the VI pathway helps evaluate (1) whether the technology is compatible with the site conditions and stakeholder objectives (e.g., cost, timeliness, sustainability, etc.) and (2) the information needed to monitor the performance of the system over the short- and long-term.

Examples of common mitigation technologies applied below the slab (e.g., sub-slab technologies), directly below or above the slab (e.g., vapor barriers), and inside the building (e.g., HVAC controls) are described in the technology information sheets mentioned in this chapter, including how they modify the VI pathway and information typically needed to evaluate the suitability and performance of the technology at a site. A technology information sheet is also provided for approaches to address VFC migration into buildings through preferential pathways (e.g., sewer lines or utility tunnels). Additional information is provided in the **Preferential Pathway Sealing and Ad Hoc Ventilation Technology Information Sheet**.

Following selection of the VI mitigation technology, subsequent considerations relate to the design, construction, and long-term monitoring and stewardship of the mitigation approach. This VI guidance provides the following fact sheets: **Design and Implementation Considerations for Vapor Intrusion Mitigation Approaches Fact Sheet**; **Quality Assurance Considerations Fact Sheet**; **Vapor Intrusion Mitigation System Operation, Maintenance, and Monitoring Fact Sheet**; and the **Vapor Intrusion Mitigation System Curtailment and Shutdown Fact Sheet**. Through the VI mitigation design, construction, and OM&M process, the VI CSM should be reevaluated to not only aid in the initial remedial and/or mitigation approach, but also to refine the performance monitoring and operating strategy over time. For more information about the VI CSM, see **Chapter 4: Conceptual Site Model** and the **Conceptual Site Models for Vapor Intrusion Mitigation Fact Sheet**. **Table 10-1** outlines the vapor intrusion mitigation system fact sheets and technology sheets.

Throughout the VI mitigation process, community engagement is a critical component for successful project implementation. Community engagement and public notification is simply the act of communicating information about the VI condition and anticipated actions to various stakeholders (e.g., property owner, tenants, and occupants). This information would include, but not be limited to,

background information on the site and VI, data or information that is triggering an evaluation/investigation, how a rapid response differs from a long-term response, what possible next steps might be, and contact information for entities that can provide more information and answer questions. It is essential to develop and implement a site-specific community engagement plan that addresses how to win trust and gain access to properties, communicate risk to potentially exposed individuals, and minimize the disruption of people's lives and businesses. For additional information, see Chapter 3: Community Engagement.

Table 10-1. Vapor intrusion mitigation system fact sheets and technology information sheets.
These resources can be found at https://itrcweb.org/vapor-intrusion-toolkit

Fact Sheet	Associated Technology Information Sheets or Fact Sheets
Rapid Response and Ventilation for Vapor Intrusion Fact Sheet	• Preferential Pathway Sealing and Ad Hoc Ventilation Technology Information Sheet • Indoor Air Treatment Technology Information Sheet • Heating, Ventilation, and Air Conditioning Modification Technology Information Sheet
Vapor Intrusion Remediation and Institutional Controls Fact Sheet	• Soil Vapor Extraction Technology Information Sheet • Multiphase Extraction Technology Information Sheet • Institutional Controls Technology Information Sheet
Active Vapor Intrusion Mitigation Systems Fact Sheet	• Sub-Slab Depressurization Technology Information Sheet • Sub-Slab Ventilation Technology Information Sheet • Sub-Membrane Depressurization Technology Information Sheet • Crawl-Space Ventilation Technology Information Sheet • Aerated Floor Void Space Systems Technology Information Sheet
Passive Vapor Intrusion Mitigation Systems Fact Sheet	• Composite Membranes Technology Information Sheet • Single-Sheet Membranes Technology Information Sheet • Epoxy Floor Coatings Technology Information Sheet • Aerobic Vapor Mitigation Barrier Technology Information Sheet • Building Design for Passive Vapor Intrusion Mitigation Technology Information Sheet
Design and Implementation Considerations for Vapor Intrusion Mitigation Approaches Fact Sheet	• Quality Assurance Considerations Fact Sheet • Appendix J: Vapor Intrusion Mitigation System Construction Quality Assurance Plan Outline • Vapor Intrusion Mitigation Systems Post-Installation Verification Fact Sheet • Vapor Intrusion Mitigation System Operation, Maintenance, and Monitoring Fact Sheet • Appendix K: Vapor Intrusion Mitigation Stewardship Plan Outline • Vapor Intrusion Mitigation System Curtailment and Shutdown Fact Sheet • Appendix L: Vapor Intrusion Mitigation Example Curtailment Plan Outline
Checklists and Templates for Active and Passive Mitigation Approaches	• Active Mitigation Checklist • Passive Mitigation Checklist • Post-Installation Vapor Intrusion Mitigation System Verification Checklist • Vapor Intrusion Mitigation System Operation, Maintenance, and Monitoring Checklist

10.1. Rapid Response

Rapid response is an interim VI mitigation approach that may be appropriate, under certain conditions (e.g., high contaminant concentrations, sensitive populations present) prior to implementing a long-term mitigation strategy for an occupied room or building. With respect to VI, a rapid response is one that could be easily implemented and verified on a timescale of days to weeks, whereas a long-term mitigation strategy typically takes longer to design and implement but is more effective, practicable, and often more cost-effective to operate over a long period of time. Some technologies or mitigation methods characterized as rapid response may also be suitable as long-term mitigation strategies.

A rapid response may be implemented prior to developing a complete VI CSM. Acceptable rapid response methods can vary based on site location and building use; however, a good understanding of building occupant demographics and building use is helpful to evaluate the need for and type of rapid response. For cases where VFCs are detected in indoor air at concentrations exceeding short-term exposure criteria, a rapid response may be required (Beringer 2017; USEPA 2015b). Rapid response actions can include administrative controls, such as relocating occupants and eliminating occupant access to the building, or ECs that reduce chemical vapor exposure through building ventilation, indoor air treatment, or by physically preventing vapor entry into the building.

The requirement for a rapid response can vary significantly from state to state and among regulatory programs or health agencies. The criteria that may trigger the need for a rapid response and the time frame that qualifies a response as rapid also vary among jurisdictions. The **Rapid Response and Ventilation for Vapor Intrusion Fact Sheet** presents approaches and methods that should be considered when a rapid response has been deemed necessary.

The scope of the **Rapid Response and Ventilation for Vapor Intrusion Fact Sheet** is limited to scenarios where there may be an acute risk to human health from VFCs and does not include emergency situations (i.e., call 911 situations) where combustible, explosive, or oxygen-deficient conditions may exist inside a building. Depending on the regulatory framework and the measured indoor or subsurface concentrations for the VFCs, similar terms may include accelerated response, urgent response, or expedited response. Within a given regulatory framework, these terms may have slightly different definitions based on the indoor air concentrations and/or site-specific conditions; however, each of these terms should be considered under the umbrella term of rapid response, as the definitions are distinctly different from emergency scenarios requiring an immediate call to 911 (e.g., due to combustible gases in indoor air or oxygen-deficient conditions). Emergency conditions fall outside the scope of this document.

The **Rapid Response and Ventilation for Vapor Intrusion Fact Sheet** includes the following information:

- An overview of rapid response as a preliminary method to consider
- A description of the typical options related to rapid response
- The advantages and limitations of implementing a rapid response
- General cost considerations related to rapid response
- Other special circumstances to consider when deciding whether rapid response is applicable

For more detailed technical information on specific rapid response options, see the ITRC **Preferential Pathway Sealing and Ad Hoc Ventilation Technology Information Sheet**, **Indoor Air Treatment Technology Information Sheet**, and **Heating, Ventilation, and Air Conditioning Modification Technology Information Sheet**.

10.1.1. Occupant, Community, and Stakeholder Considerations

During a rapid response situation, the practitioner may not have had sufficient time to have made contact with and develop a relationship with the occupants, community, and other stakeholders that are generally established during the course of a project. It is essential to develop and implement a site-specific community engagement plan (CEP) that addresses how to win trust and gain access to properties, communicate risk to potentially exposed individuals, and minimize the disruption of people's lives and businesses.

Public notification examples may include communications with property owners, tenants, or inter-agency communication (e.g., the state environmental agency notifies the state health department). Instances that require immediate action should be broached in a more succinct directive without causing undo panic. Transparency in expedited responses may require communicating incomplete information with follow-up as more information becomes available. For more details, see **Chapter 3: Community Engagement** and the **Design and Implementation Considerations for Vapor Intrusion Mitigation Approaches Fact Sheet**.

10.2. Remediation and Institutional Controls

Some VI investigations and regulatory requirements may indicate that different types of corrective actions should be taken to reduce the indoor air concentrations to acceptable levels. Remediation commonly refers to an action that reduces the level of contamination in the environmental medium (e.g., soil, groundwater) that is acting as the source of VFCs in indoor air. Mitigation, on the other hand, is generally applied to actions that prevent or limit human exposure to VFCs. Further discussion on mitigation versus remediation is provided in the **Vapor Intrusion Remediation and Institutional Controls Fact Sheet**, which describes the following:

- The use of remediation systems and ICs as a means of VI mitigation
- Differences between remediation and mitigation
- Various remediation methods that can serve as VI mitigation options
- Benefits and disadvantages of ICs and remediation as mitigation
- Additional considerations for assessing the impact of remediation on VI mitigation

ICs can also provide protection and serve as an administrative assurance for mitigation of a known or potential VI concern. This guidance will help the reader evaluate the applicability of environmental remediation and ICs as a means of VI mitigation.

10.2.1. Remediation as Vapor Intrusion Mitigation

In some instances, environmental technologies designed for source remediation can also serve as VI mitigation. For remediation to serve dually as VI mitigation and achieve site cleanup objectives, it must accomplish the same objective as a VIMS, which is to reduce concentrations of VFCs in indoor air below the applicable regulatory levels. Remediation technologies that potentially can serve this purpose include SVE and MPE. An overview of each of these technologies is presented below, and in the **Vapor Intrusion Remediation and Institutional Controls Fact Sheet**.

Soil Vapor Extraction (SVE) Technology
SVE is a remediation technology that is designed to remove contaminants that are adsorbed onto soils by imparting a vacuum on the impacted soils and flushing out the contaminants that have been moved from

the soil and into soil vapor. In an SVE process, extraction wells and/or trenches connect to blowers through piping. For additional information on SVE, refer to the **Soil Vapor Extraction Technology Information Sheet**.

Multiphase Extraction (MPE) Technology
MPE is a remediation technology that relies on the extraction of contaminants present in liquids (groundwater and free product) and adsorbed to soils to reduce or eliminate the source of VFCs in the subsurface. For additional information on MPE, refer to the **Multiphase Extraction Technology Information Sheet**.

10.2.2. Institutional Controls as Vapor Intrusion Mitigation

ICs are a form of LUCs that provide protection from exposure to site-related contaminants. While ICs consist of administrative or legal restrictions on a site, LUCs can also use physical measures, which are ECs (e.g., physical barriers). In contrast to ECs, ICs are primarily government controls, proprietary controls (e.g., deed restrictions), enforcement or permit mechanisms, and informational devices. Planning that protects human health and the environment and uses all aspects of an IC life cycle is essential for long-term success (e.g., a long-term stewardship plan). In relation to the VI pathway, ICs can be applied as a stand-alone remedy (for undeveloped lands or restricted use on developed land), as part of an overall remedy selection, or as a mechanism that requires ongoing monitoring and maintenance of the mitigation system. More details are provided in the accompanying **Vapor Intrusion Remediation and Institutional Controls Fact Sheet** and the **Institutional Controls Technology Information Sheet**.

For further information on the various types of ICs, also refer to ITRC's *Long-term Contaminant Management Using Institutional Controls* (ITRC 2016).

10.2.3. Other Considerations

Some types of remediation, while not directly employed with the intent to directly remediate the soil vapor, may influence the operation of the existing or future VIMS. Some examples include the following:

- Addressing the source of VI impacts, such as contaminated soils, NAPL, or groundwater (e.g., through excavation, sparging, in situ treatment, hydraulic containment) may result in the reduction of soil VFC concentrations and the time frame when VI mitigation needs to be conducted.
- Performing remediation using technologies that result in the generation of emissions or altering of the soil vapor flow patterns (e.g., sparging, in situ chemical treatment, thermal treatment) may alter the VI CSM and influence a VI mitigation strategy.

Due to the potential threat/liability posed by identified, ongoing VFC sources, regulatory agencies may request that the following actions be taken:

- Implement interim measures before design and implementation of a VI mitigation strategy.
- Implement remedial actions on undeveloped land or unoccupied buildings prior to implementing VI mitigation at new construction or re-occupancy of existing buildings.
- Design and implement a VI mitigation strategy prior to commencing certain remediation actions that may have the potential to exacerbate VI (e.g., releasing additional vapor, formation of daughter products into the vadose zone, etc.).
- Conduct remediation independently of the VI mitigation

For further information see the Vapor Intrusion Remediation and Institutional Controls Fact Sheet and the Design and Implementation Considerations for Vapor Intrusion Mitigation Approaches Fact Sheet.

10.2.4. Occupant, Community, and Stakeholder Considerations

Effective VI mitigation at the project site requires proactive community engagement. As previously discussed, carefully designed public outreach as part of a site-specific CEP is an essential part of any aspect of the VI response. This includes ICs, informational devices, and remedial actions. ICs may be established to ensure the occupants, owners, and managers are informed and involved as partners in the long-term management of VIMS and performance monitoring of the affected building. For more details see Chapter 3: Community Engagement and the Design and Implementation Considerations for Vapor Intrusion Mitigation Approaches Fact Sheet.

10.3. Active Vapor Intrusion Mitigation Systems

Active mitigation of the VI pathway involves continuous interception, dilution, or diversion of soil vapor entry into a building using mechanical means that are powered by electricity. The performance of an active VIMS is quantifiable by measurement of vacuum, area of influence, post-installation indoor air sampling, VIMS inspection, flow rates, and/or mass flux (i.e., the mass of a chemical passing through a defined cross-sectional area over a period of time).

The Active Vapor Intrusion Mitigation Systems Fact Sheet presents information on the design, installation, and OM&M of active mitigation technologies for both new construction and existing buildings that range from small (e.g., residential) to comparatively larger (e.g., commercial/industrial) buildings. The mitigation technologies presented in the Active Vapor Intrusion Mitigation Systems Fact Sheet assume the primary means for soil vapor entry is via advection rather than diffusion.

VIMS that are active are designed to achieve either depressurization of the sub-slab soil or granular fill relative to indoor air or some degree of airflow and dilution in the sub-slab space (i.e., ventilation). Active mitigation systems designed for depressurization will also achieve some degree of ventilation, and active mitigation systems designed for ventilation may also achieve some degree of depressurization. These two types of technologies (depressurization and ventilation) are not separate and distinct, but they are monitored using different performance metrics and criteria. Additionally, both technologies will remove some vapor mass by means of moving impacted vapors from the subsurface; however, mass removal is not the intent of an active VIMS design and likely will not remove the sorbed source mass as is intended for remediation technologies (e.g., SVE). It is important to note that surface contamination of the slab and some preferential pathways will not be sufficiently addressed by sub-slab depressurization or ventilation; additional details can be found in the Sub-Slab Depressurization Technology Information Sheet and the Sub-Slab Ventilation Technology Information Sheet.

Active mitigation for new construction can be significantly different from existing buildings due to components of new buildings and control of the design and installation of the system during construction of the building. Additionally, buildings vary widely in size, function, and use. Because of this variability, implementation of active mitigation technologies will also vary widely, depending on the type of building and the design objectives for the VIMS. Details and differences between active mitigation for new construction and existing buildings are listed in the Active Vapor Intrusion Mitigation Systems Fact Sheet, the Design and Implementation Considerations for Vapor Intrusion Mitigation Approaches Fact Sheet, the Vapor Intrusion Mitigation Systems Post-Installation Verification Fact Sheet, and the Vapor Intrusion Mitigation System Curtailment and Shutdown Fact Sheet.

10.3.1. Common Active Mitigation Strategies

Active mitigation involves the use of energized controls (e.g., a fan/blower) to maintain acceptable indoor air quality by mitigating the potential for VI into a building. There are multiple different methods for active mitigation; the most common methods are listed below:

- Sub-slab depressurization (SSD)
- Sub-slab ventilation (SSV)
- Sub-membrane depressurization (SMD)
- Crawl-space ventilation (CSV)
- Aerated floor void space systems (VSS)

The **Active Vapor Intrusion Mitigation Systems Fact Sheet** and associated **Sub-Slab Depressurization Technology Information Sheet**, **Sub-Slab Ventilation Technology Information Sheet**, **Sub-Membrane Depressurization Technology Information Sheet**, **Crawl-Space Ventilation Technology Information Sheet**, and **Aerated Floor Void Space Systems Technology Information Sheet** summarize the many considerations for the design, installation, verification, and OM&M of each of the most common active mitigation technologies.

10.3.2. Considerations for Design and Implementation

Many considerations and decisions are necessary to select, design, install, operate, and eventually decommission an effective active mitigation system. These considerations are outlined in the **Active Vapor Intrusion Mitigation Systems Fact Sheet**, which provides a summary of information to consider during each step in the active mitigation process. More details regarding each consideration can be found in the **Design and Implementation Considerations for Vapor Intrusion Mitigation Approaches Fact Sheet**, **Quality Assurance Considerations Fact Sheet**, and **Vapor Intrusion Mitigation System Curtailment and Shutdown Fact Sheet**.

Buildings vary widely in their size, function, and use; therefore, the implementation of VI mitigation technologies will vary widely depending on the type of building for which the VI mitigation is needed and the intended design objectives of the VI mitigation. The design considerations should also account for long-term stewardship of active VIMS. Active VIMS should be intentionally designed and installed inclusive of procedures and guidance (or in some cases, ICs) put in place to maintain the operation of these systems until such a time that the system can be considered for shutdown (if ever).

10.3.3. Post-Installation Performance Verification

Following design and installation, the mitigation system will be turned on, and verification will be needed to document that the system is operating according to the design objectives. Verification of system installation and effective operation may include multiple criteria. It is also important during this step, as well as in the future during performance monitoring, to confirm the CSM for which the system was designed. The **Active Vapor Intrusion Mitigation Systems Fact Sheet** and **Vapor Intrusion Mitigation Systems Post-Installation Verification Fact Sheet** provide a summary of possible post-installation verification considerations that may be needed for active mitigation approaches.

10.3.4. Vapor Intrusion Mitigation Systems Operation, Maintenance, and Monitoring

After the mitigation strategy has been selected, designed, and commissioned, the OM&M plan plays a key role in demonstrating the ongoing effectiveness of the VIMS. The accompanying **Vapor Intrusion Mitigation System Operation, Maintenance, and Monitoring Fact Sheet** describes the key considerations of VIMS OM&M. Complex mitigation strategies will typically require more complex OM&M procedures. The key to OM&M is to gather data to support maintaining the VIMS to operate as designed, with the goal that it remains effective in the short and long term until it is appropriate to implement a curtailment strategy, if appropriate.

10.3.5. Occupant, Community, and Stakeholder Considerations

Carefully designed public outreach is an essential part of any aspect of the VI response. Effective VI mitigation at the project site requires proactive community engagement. It is essential to develop and implement a site-specific CEP that addresses how to win trust and gain access to properties, communicate risk to potentially exposed individuals, and minimize the disruption of people's lives and businesses. This includes ICs, informational devices, and remedial actions.

Owners, tenants, and other parties (including contractors and architects for new buildings) often have strong opinions about the aesthetic effects and inconvenience experienced with the location of mitigation system components, including fans, pipe runs, and vent stacks. Stakeholders should be engaged, and their considerations incorporated into the system design as early as practical. ICs may be established to ensure the occupants, owners, and managers are informed and involved as partners in the long-term management of VIMS and, if necessary, performance monitoring of the affected building. For more details see **Chapter 3: Community Engagement** and the **Design and Implementation Considerations for Vapor Intrusion Mitigation Approaches Fact Sheet**.

10.4. Passive Vapor Intrusion Mitigation Systems

Passive mitigation of the VI pathway involves interception, dilution, diffusion, or diversion of soil vapor entry into a building without the use of mechanical means. These systems physically block the entry of vapors into a building and/or rely on natural mechanisms, such as chemical diffusion and thermal- or wind-induced pressure gradients, to divert VFCs and soil vapor around the building (e.g., to riser pipes). Passive VIMS require a high degree of documentation during the installation process, an OM&M phase to ensure a fully sealed barrier is installed and maintained, and establishing planning methods to confirm the system's effectiveness, such as using surrogates and tracers (e.g., smoke testing).

The **Passive Vapor Intrusion Mitigation Systems Fact Sheet** and **Passive Vapor Intrusion Barriers Fact Sheet** provide information related to passive mitigation approaches, and more detailed information about each passive approach can be found in several technology information sheets. Links to technology sheets can be found at **https://itrcweb.org/vapor-intrusion-toolkit**.

- Common passive barriers systems
  - Composite Membranes Technology Information Sheet
  - Single-Sheet Membranes Technology Information Sheet
  - Epoxy Floor Coatings Technology Information Sheet
- Common passive venting systems
  - Sub-Slab Ventilation Technology Information Sheet

  - Aerated Floor Void Space Systems Technology Information Sheet
- Building Design for Passive Vapor Intrusion Mitigation Technology Information Sheet

10.4.1. Considerations for Design and Implementation

Effective passive VI mitigation can sometimes be accomplished through building design. Building design for passive VI mitigation includes the construction of vented parking garages or raised foundations between a subsurface source of vapors and an occupied space intended for living or working. Building design for VI mitigation is strategically engineered ventilation built into the building. A building designed with a foundation that will inherently provide an increased level of mitigation and ventilation is a type of passive mitigation that does not rely on sub-slab membrane barriers with SSV systems.

The **Building Design for Passive Vapor Intrusion Mitigation Technology Information Sheet** provides basic information about relying upon building design for passive mitigation of VI and discusses advantages, limitations, and associated cost considerations of building design to mitigate VI risks. This technology sheet also describes the basic components of building design for the purpose of VI mitigation, design considerations, and verification of ventilation when constructing buildings designed to mitigate potential VI risks.

10.4.2. Occupant, Community, and Stakeholder Considerations

As with other VI mitigation methods, a carefully designed public outreach is an essential part of any aspect of the VI response. Occupants of buildings with existing passive mitigation measures should be made aware of potential VI risks and that the design features (e.g., passive ventilation and sub-slab passive barriers) provides a level of protection designed to prevent VI from occurring.

Communication with the property owner on their expectation of the design, if any, early in the design process will help to avoid problems during installation and operation. Occupants should be instructed to avoid modifying the concrete slab to prevent affecting the function of the passive barrier. When planning modifications to a building with a passive barrier, consideration should be given to whether the modifications will affect the integrity of the barrier. ICs must be established to ensure the occupants, owners, and managers are informed and involved as partners in the long-term management of VIMS and, if necessary, performance monitoring of the affected building. For more details see **Chapter 3: Community Engagement** and the **Design and Implementation Considerations for Vapor Intrusion Mitigation Approaches Fact Sheet**.

10.5. Considerations for Design and Implementation of Vapor Intrusion Mitigation Approaches

10.5.1. Design and Implementation Considerations

Multiple factors affecting the suitability and efficacy of a VIMS should be considered during the design, review, and approval process. The selected technology should be based on a good understanding of the VI CSM and be able to meet the remedy objectives pertaining to soil vapor conditions at the site, whether applying an active VIMS, passive VIMS, rapid response, and/or environmental remediation technology. ITRC has developed a series of fact sheets that summarizes and describes the most common design considerations for active VIMS, passive VIMS, and environmental remedial technologies that need to be considered as part of any design process.

The design process should begin with a consideration of the VI CSM elements applicable to VI mitigation and the remedy objectives, leading to the design basis (i.e., an explanation of how the selected approach and technologies will meet the remedy objectives at the site); see the **Conceptual Site Models for Vapor Intrusion Mitigation Fact Sheet** for additional discussion. In many cases, this review indicates that additional information is needed for the design of a specific type of VIMS; therefore, the need for predesign investigations and/or testing should be considered. Once sufficient information is available for design, the next consideration is the design itself—the area that requires mitigation along with the system components, installation details, and specifications. Other design considerations include installation and operating permitting requirements; stakeholder requirements and communications; and the need for construction quality assurance (CQA), demonstration of system effectiveness and reliability, and the development of OM&M plans, including a potential long-term curtailment strategy. For further details see the **Design and Implementation Considerations for Vapor Intrusion Mitigation Approaches Fact Sheet**.

10.5.2. Construction Quality Assurance

CQA of a VIMS should be performed to provide documentation that the VIMS is installed as designed with the components and materials specified and to provide standard procedures for resolving deviations from the provided design plans and specifications. A CQA plan is a VIMS-specific plan outlining the information that an on-site engineer, site manager, or equivalent, should document at each step during installation. Some jurisdictions and product manufacturers may have specific CQA requirements that should be included in a CQA plan. For more information, please see the **Quality Assurance Considerations Fact Sheet**.

10.5.3. Post-Installation Verification

After the implementation of a mitigation strategy, post-installation verification and testing to confirm achievement of the design and operating parameters should be performed. It is during this time that the CSM may be further refined, and the VIMS is confirmed to be operating and meeting performance specifications (potentially using multiple approaches or criteria). Post-installation verification and testing can identify deficiencies or failures in the VIMS, and it may be possible to address such issues prior to building occupancy. The **Vapor Intrusion Mitigation Systems Post-Installation Verification Fact Sheet** describes the most common post-installation considerations for active VIMS, passive VIMS, rapid response, and/or environmental remediation technologies that need to be considered as part of the mitigation system verification testing process.

10.5.4. Operation, Maintenance, and Monitoring

VIMS are typically used as long-term measures that can reliably reduce and/or prevent human exposure to VFCs in indoor air resulting from VI if the system is continuously and properly operated in accordance with design specifications and regularly inspected and maintained. The monitoring component of OM&M, which can be recommended by the system manufacturer, standard industry practice, site-specific risk factors, and/or the regulatory authority, serves short- and long-term purposes:

1. **Short term:** The monitoring data can support the conclusion that the system is operating as intended or that there may be an issue in the VIMS that must be addressed, (e.g., pipe blockage, inoperable mechanical equipment).

2. **Longer term:** The monitoring data can be used to evaluate whether VIMS operation and/or monitoring requirements can be curtailed or eventually shutdown.

The **Vapor Intrusion Mitigation System Operation, Maintenance, and Monitoring Fact Sheet** describes the most common OM&M considerations for active VIMS, passive VIMS, and rapid response approaches

that include ECs, and environmental remedial technologies that need to be considered as part of the design process.

10.6. Vapor Intrusion Mitigation Curtailment and Closure Strategies

A key concept throughout the process of designing, implementing, and operating a VIMS is using monitoring data to optimize system operation over time and evaluating monitoring data, improving the understanding of the VI CSM, and potentially supporting a case for a reduction in monitoring scope, system curtailment, and/or monitoring termination. It is recognized that in some cases the continued operation of an active or passive VIMS may be required indefinitely to ensure the ongoing protection of building receptors. This can be achieved using a managed closure strategy that incorporates long-term OM&M and/or ICs, which should remain until either the VI pathway is eliminated, detected concentrations of VFCs in applicable media are reduced to below applicable target levels, and/or a curtailment plan is successfully completed, thereby rendering restrictions on land or building use no longer justified (see **Section 11.5**). In other instances, the data may demonstrate that the VIMS is no longer necessary and monitoring requirements can be eliminated entirely, resulting in unrestricted closure with respect to VI (see **Section 11.5**).

The **Vapor Intrusion Mitigation System Curtailment and Shutdown Fact Sheet** presents a framework to consider for optimizing the monitoring and operation of a VIMS based upon long-term site management objectives while prioritizing effective management of the VI pathway. The objectives in this document may not be appropriate to consider for every site. Conceptual approaches for VIMS curtailment may include (1) a reduction of ongoing system monitoring requirements, (2) a transition from active to passive system operation, and/or (3) termination of the ongoing VIMS monitoring and/or operation.

The ongoing OM&M and ICs for VI management can be terminated when protective measures are no longer necessary to safeguard human health. This decision is data driven and based on assessments of current exposures and anticipated future exposures. Regardless of the exact scenario, modification of system operation or the selection of a curtailment strategy will depend on site-specific conditions and should be approached as a process based upon the use of MLE to evaluate and demonstrate the effective operation of the VIMS and/or to provide justification that ongoing VIMS OM&M is no longer warranted. The OM&M plan should clearly define the closure criteria (e.g., cleanup levels for the vapor source) and provide guidance for phased decommissioning of the VIMS(s). MLE should be used to support decision-making, and some MLE may be more appropriate or applicable than others depending upon the site and regulatory conditions. For these reasons, the reader is encouraged to refer to the **Multiple Lines of Evidence Fact Sheet**, the **Vapor Intrusion Mitigation System Operation, Maintenance, and Monitoring Fact Sheet**, and the **Conceptual Site Models for Vapor Intrusion Mitigation Fact Sheet** in addition to the **Vapor Intrusion Mitigation System Curtailment and Shutdown Fact Sheet**.

VI mitigation curtailment approval, the ability and authority to remove an IC, and closure strategy acceptance may vary from jurisdiction to jurisdiction. It is best practice to engage with the regulatory agency early in the project to understand what is required for closure. Stakeholder notifications should be made to the appropriate regulatory agencies and private entities that closure criteria have been met and that OM&M and/or the ICs have been or can be discontinued. For further discussion on closure strategies and requirements related to the VI pathway in general see **Chapter 11:Vapor Intrusion Component Determination, Exit Points, and Closure**.

CHAPTER 11: VAPOR INTRUSION COMPONENT DETERMINATION, EXIT POINTS, AND CLOSURE

The ultimate goal of a VI project is to understand the potential for VI to affect current/future building(s) at the site, implement a management strategy for the VI pathway as applicable, or mitigate such a pathway to the extent feasible such that potential VI risk associated with the pathway is below relevant risk limits. The possible routes to VI closure should be considered starting at the beginning with the preliminary assessment and reassessed throughout the investigation, evaluation, and mitigation phases, as applicable. VI closure can be achieved in two forms with unrestricted VI closure or managed VI closure.

VI closure refers to the unrestricted completion of a VI project due to the elimination of potential complete VI pathways such that VFCs are below the applicable screening levels and no mitigation measures or ICs are required to protect current or future building receptors. In contrast, a managed VI closure of a site refers to the completion of a project under some form of long-term restrictions. Section 11.5 describes managed VI closure strategies aimed at achieving regulatory closure (jurisdictionally defined) where the need for VI mitigation (e.g., VIMS, building modifications), ongoing monitoring and reporting, and/or ICs are required to protect current and/or future building receptors.

Unrestricted VI closure is an exit strategy that allows for the termination of all monitoring, remedial activities, VI mitigation, and ICs resulting from eliminating and/or reducing VFC concentrations and meeting remedial action objectives for the VI component at the site. A managed VI closure could be implemented as either an intermittent or long-term strategy (e.g., ICs, deed restrictions, permanent building modifications, etc.) to eliminate (or mitigate to the extent feasible such that associated risk is also managed) the VI pathway indefinitely, requiring adherence to property restrictions and/or implementation of long-term OM&M plans, stakeholder management, or CEPs. This section will discuss several different closeout strategies that can be reviewed during each VI project stage.

This chapter focuses on the closure strategies for the VI pathway, which may be only one component of the site. Overall site closure should consider all contaminated media and be discussed with the applicable regulatory agency before determining conclusions.

11.1. Overview

Concluding a VI project requires understanding the presence of VFCs and the complex relationships among subsurface conditions (e.g., geology, utilities, groundwater, soil, soil vapor, etc.), complete or potentially complete VI pathways, and current/future buildings. VI project conclusions will depend on current and future site conditions and property use. A comprehensive approach is necessary to assess the intricate relationships among groundwater, soil, soil vapor, and indoor air. These evaluation methods can be used to make a sound, technically defensible determination as to whether the VI pathway is complete, potentially complete, or incomplete and warrants no further investigation; evaluate the potential risk associated with pathways that are found to be complete; and inform decision-making about next steps, such as further investigation, remediation, or mitigation. For more information regarding identification of VFCs and completed pathway determination see Chapter 2: Vapor Intrusion 101.

VI projects can be viewed in stages, aligned with those of the VI life cycle described in the Chapter 4: Conceptual Site Model, and, depending on where the VI project is in the cycle, the data and MLE necessary to reach the conclusion of the VI project will vary. Informed decision-making relies on an up-to-date accurate CSM that is essential for ensuring the success of environmental site management efforts. A review of the comprehensive CSM at the end of each VI project stage should be conducted and discussed with the applicable regulatory agency before determining conclusions. For more information see Chapter 4: Conceptual Site Model.

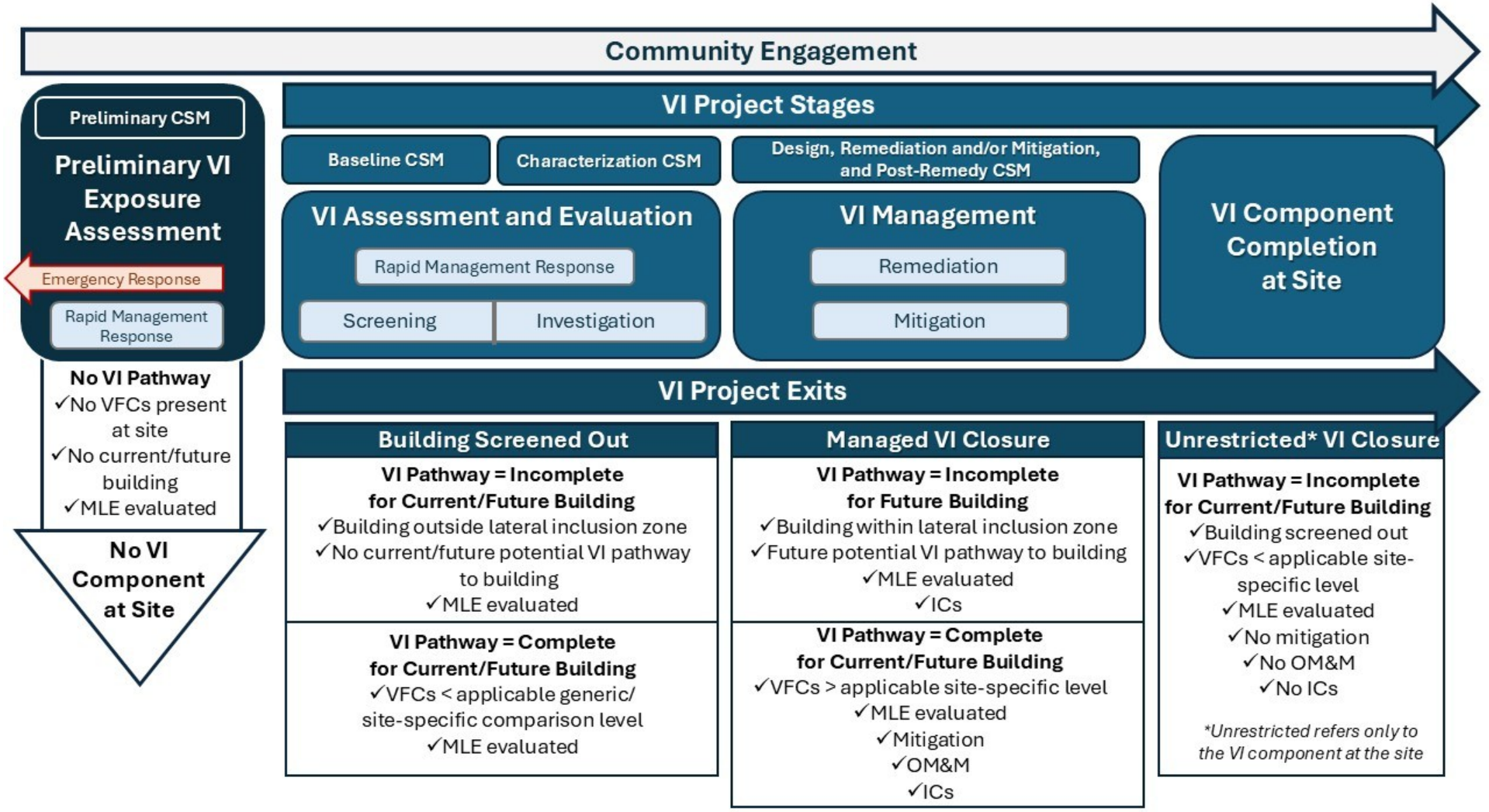
The VI pathway assessment process provides a consistent approach to VI that fits the applicable regulatory framework, VFC, and type of site, and it is critical for confident decision-making that protects human health. Figure 11-1 illustrates the process flow chart for VI project stages from the preliminary exposure assessment through VI component completion at a site (Figure 11-1 was originally presented as Figure 2-9). High-level descriptions of the different components of the process (i.e., Project Stages) are provided in Section 2.3 Vapor Intrusion Pathway Assessment Process.

At the conclusion of each VI project stage, the VI project team should use an MLE approach and determine whether the VI pathway is incomplete, potentially complete, or complete and the risk to current and future building receptors. Figure 11-2 depicts the typical VI project stages and MLE collected at each stage that support the decision to either continue the VI project onto the next stage or conclude the VI project—that is, demonstrate that the site has been screened out of further VI investigation or management, emphasizing the opportunity to exit during each project stage. It is possible to apply a conclusion to the entirety to the site, a portion of the site, or a building. This chapter provides information on the conclusion part of each stage. For more information on the various methods for evaluating data see Chapter 8: Data Evaluation and Vapor Intrusion Risk Assessment and see the Multiple Lines of Evidence Fact Sheet for a detailed discussion of the MLE approach.

Federal, state, and local regulatory requirements, policies, and guidance may vary and result in different closure strategies. In addition, some jurisdictions may provide guidance that is not recognized in other jurisdictions, and the best practice is to engage with the regulatory agency at the beginning of the VI project to understand best practices and VI closure requirements for the site (see Appendix A: Summary of State Vapor Intrusion Practices).

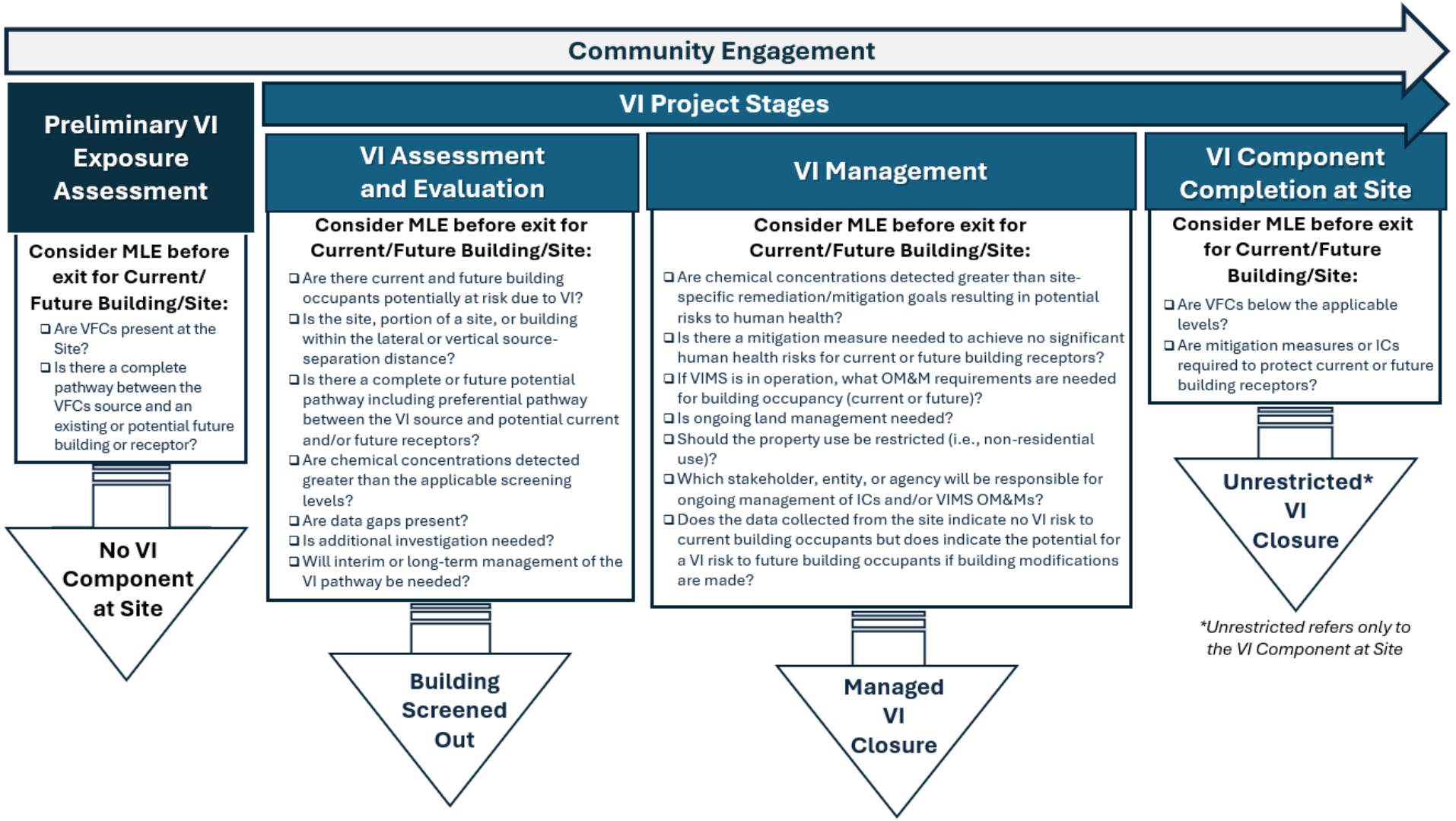
11.2. Community Engagement Considerations

Successfully implementing a VI exit strategy for a VI project requires proactive community engagement that communicates information about the VI component, anticipated actions to various stakeholders (e.g., property owner, tenants, and occupants), the closure decision, and considerations from the community. It is important to help stakeholders understand that unrestricted VI closure is not always possible and that mitigation may still be needed. Incorporating this understanding into the communication plan will aid in implementing a managed VI closure exit strategy without any surprises at the end. In addition, any changes to or discontinuation of the VIMS will need to be communicated and discussed with stakeholders. If community engagement is started early, stakeholders should be aware that VIMS operation may not be required in perpetuity as discussed in the Vapor Intrusion Mitigation System Curtailment and Shutdown Fact Sheet. Further, if ownership or occupancy changes, new stakeholders should be informed of VIMS status and operation and exit strategy. See Section 3.5 Mitigation (Remedy Needed) and Section 3.6 Long-Term Stewardship Best Practices for more information.



Notes: CSM = conceptual site model; IC = institutional control; MLE = multiple lines of evidence; OM&M = operation, maintenance, and monitoring; VFC = vapor-forming chemical; VI = vapor intrusion.

Figure 11-1. Vapor intrusion pathway assessment process.



Notes: IC = institutional control; MLE = multiple lines of evidence; OM&M = operation, maintenance, and monitoring; VFC = vapor-forming chemical; VI = vapor intrusion; VIMS = vapor intrusion mitigation system.

Figure 11-2. Component determination, exit points, and closure strategies.

11.3. No Vapor Intrusion Component Determination

A preliminary VI exposure assessment determines whether there is a VI component or no VI component at a site by assessing the presence of VFCs in the subsurface, the potential linkage between the VFC source and a current or future building (receptor) across a site, and whether VFCs are present or present at levels that necessitate emergency or rapid response. For additional information see **Section 5.2.1, Preliminary Vapor Intrusion Exposure Assessment**.

To determine whether there is no VI component at a site, the following should be considered:

- Are VFCs present at the site?
- Is there a complete pathway between the VFC source and an existing or potential future building or receptor?

If **neither** of these conditions are present, sites where no VFCs are present and a completed or potentially complete pathway was not identified, it can be concluded that there is no VI component at the site. Therefore, no action or further evaluation is required (see **Figure 11-2**). For more information regarding the identification of VFCs and completed pathway determination, see **Chapter 2: Vapor Intrusion 101**.

When potential or known VFC(s) are present at a site and a completed or potentially completed pathway between a potential VI source and an existing or potential future building has been determined, it means a VI component has been identified. As a result, additional evaluation is warranted, and the initial VI screening process should begin (see **Section 5.3**).

11.4. Site Screening and Data Evaluation

For sites where a VI component was identified, a site, portion of a site, or a building can be screened out from further investigation or management during the VI screening or investigation stage if it is concluded there is no complete or future potential VI pathway, a completed pathway is mitigated, and/or risks for complete pathway receptors are below applicable thresholds. As discussed in **Chapter 5: Site Screening**, the goal of VI screening is to determine whether the potential for VI exposure warrants further evaluation, mitigation, or remediation or whether VI exposure can be ruled out based on a limited or preliminary VI CSM. Not all VI components require detailed and comprehensive CSMs; however, MLE should be considered (see the **Multiple Lines of Evidence Fact Sheet**). For example, PVI components at a site can often be screened out simply based on source-building separation distance (i.e., pathway evaluation) (see **Section 5.2.2 Screening Data Evaluation**).

For sites where a VI component was identified by the presence of potential or known VFCs and a corresponding completed or future potential VI pathway to an existing or potential future receptor, the VI screening process should evaluate additional conditions to determine whether a site can be screened out.

For a site, portion of a site, or building that cannot be screened out, further investigation or management will be needed, and the following questions should be considered:

- Are there current and future building occupants potentially at risk due to VI?
- Is the site, portion of a site, or building within the lateral or vertical source-separation distance?
- Is there a complete or future potential VI pathway including preferential pathways between the VI source and potential current and/or future receptors?
- Are chemical concentrations detected greater than the applicable screening levels?

- Are data gaps present?
- Is additional investigation needed?
- Will interim or long-term management of the VI pathway be needed?

If none of these conditions are met at the site, portion of a site, or building, it can be concluded that VI pathway is incomplete and there is no current or future risk to potential receptors; therefore, further investigation or management is not needed, the site can be screened out, and no further action warranted.

The VI project team should use the MLE approach and determine whether the VI pathway is incomplete or complete and determine the risk to current and future building receptors. It is possible to apply a conclusion to the entirety of the site, a portion of the site, or a building. Additionally, federal, state, and local regulatory requirements, policies, and guidance may vary and result in either approval or denial of different closure approaches. It is recommended that practitioners engage with the applicable regulating authority prior to making final determinations. For more details see **Chapter 5: Site Screening** and **Chapter 4: Conceptual Site Model**. Additional guidance is also provided in the **Multiple Lines of Evidence Fact Sheet**.

11.4.1. Data Evaluation and Vapor Intrusion Risk Assessment

The goal of investigating the VI pathway is to determine whether the pathway is incomplete or complete (see **Section 2.1.1**) and, if the pathway is complete, evaluate the risk to current and future building receptors. When evaluating data collected as part of the VI investigation and weighing the MLE, it must be determined whether there is sufficient information and data to first reach a conclusion about whether the pathway is complete or has the potential to become complete in the future, and if so, conduct a VI risk assessment that can be used to support decision-making for remediation and/or mitigation.

This process includes evaluating the data obtained from the investigation activities and assessing VI risk. For this document, VI risk assessment can include applying generic/default screening levels to screen concentrations or perform screening risk calculations and conducting site-specific risk assessments. If the pathway is incomplete or risks are below applicable thresholds, mitigation and further evaluation may not be required; however, remediation may still be necessary to address potential future VI. Specific next steps to be taken after data evaluation and risk assessment will depend on regulatory requirements, so state and/or federal VI guidance that is applicable to the site should be consulted, and decisions should be made in consultation with applicable regulatory authorities, if warranted. Some key elements of assessing data quality and evaluating data are summarized in **Chapter 8: Data Evaluation and Vapor Intrusion Risk Assessment**. Data quality is also addressed by the **Data Quality and Adequacy Fact Sheet**. Key data evaluation steps can include (but may not be limited to) evaluating data in the context of the site CSM, comparing concentration data to default or site-specific screening levels, using site data to conduct a screening risk assessment or site-specific risk assessment, and developing MLE to support the conclusions reached as an outcome of the evaluation process.

Upon execution of the work plan and review of the results, the investigator should first determine whether the site has been adequately characterized. Have the COCs been properly delineated? Has the potential for VI at all possibly affected buildings been assessed? Are there sufficient data to perform a VI evaluation, conduct a risk assessment, and then reach a remedial decision at the site? If the answers to these and similar questions are yes, the investigator can move on to consider whether mitigation is warranted.

If such a data evaluation identifies data gaps that prevent reaching a final conclusion at the site, additional investigations are warranted, and the process returns to developing a new work plan for the

next round of investigation. Keep in mind that subsequent work plans can focus on the scope of work and rely on previously approved methods. At any point in the process, many state and federal agencies will allow a responsible party to implement a remedial action to address VI, even prior to confirming the pathway is complete, especially if concentrations potentially pose an acute or short-term exposure risk. This proactive approach can be viewed as responsive to the concerns of public health. Alternatively, the decision may be made to conduct long-term monitoring, particularly for undeveloped parcels, until such time as the VI pathway source is remediated or future development will likely introduce receptors (people) who could be exposed to unacceptable indoor contaminants from VI. For further information see **Chapter 8: Data Evaluation and Vapor Intrusion Risk Assessment** and **Chapter 9: Modeling**.

11.4.2. Vapor Intrusion Mitigation

The objective of VI mitigation is to prevent and/or reduce the severity of the migration of VFCs into a building from the subsurface. Typically, VI mitigation is implemented when it is determined that human health risks are above the applicable regulatory threshold(s) under current and/or foreseeable future conditions and the mitigation measures were implemented as part of an early action strategy, or as part of preemptive mitigation—mitigation implemented where subsurface concentrations are above remedial action objectives but indoor air concentrations are below. Project stakeholders and regulators should consider early in the project how to determine when VI mitigation is no longer required. The CSM should be used to help determine an effective site management strategy. Regardless of the management tools used, the CSM should be refined and the VI pathway reevaluated as conditions change or new information becomes available. VI mitigation implementation, design considerations, and curtailment strategies are discussed in **Chapter 10: Vapor Intrusion Mitigation**.

VI mitigation is primarily applied in the form of active or passive VIMS. Active mitigation of the VI pathway involves interception, dilution, or diversion of soil vapor entry into a building using mechanical means that are powered by electricity (see **Section 10.3, Active Vapor Intrusion Mitigation Systems**). Passive mitigation of the VI pathway involves interception, dilution, diffusion, or diversion of soil vapor entry into a building without the use of mechanical means (see **Section 10.4 Passive Vapor Intrusion Mitigation Systems**). Site closure plans and attainment/termination cleanup criteria should be developed early and will likely rely on baseline (pre-remedy) and performance (or verification) monitoring data collected during the investigation phase and the commissioning and operational phases, respectively. The cumulative data set will be used to demonstrate the attainment/target criteria were achieved. The attainment/target criteria for the chosen remedy should be comprehensive and clearly communicated in site documents. In some cases the continued operation of an active or passive VIMS may be required indefinitely to ensure ongoing protectiveness of building receptors.

In some instances, environmental remediation technologies can serve a secondary purpose as VI mitigation. Remedial technologies detailed in the **Vapor Intrusion Remediation and Institutional Controls Fact Sheet** include SVE and MPE, which includes extraction and treatment of both groundwater and soil vapors. For site remediation technologies to also serve as VIMS, they must be able to reduce concentrations of the VFCs in indoor air below the applicable regulatory levels. Alternatively, ICs or building mitigation systems can mitigate the potential for VI either as part of the site management strategy or as an interim measure also while longer-term remedies are being developed and implemented. ICs are a form of LUCs that provide protection from exposure to site-related VFCs through administrative or legal restrictions on site use, such as restrictions on residential use, schools, and/or day-care centers (see **Section 10.2, Remediation and Institutional Controls**).

The **Vapor Intrusion Mitigation System Curtailment and Shutdown Fact Sheet** presents a framework to consider for optimizing the monitoring and operation of a VIMS based upon long-term site management objectives while prioritizing effective management of the VI pathway. The objectives in this document may not be appropriate to consider for every site. Conceptual approaches for VIMS curtailment may

include (1) a reduction of ongoing system monitoring requirements, (2) a transition from active to passive system operation, and/or (3) the ultimate termination of the ongoing VIMS monitoring and/or operation.

The ongoing OM&M and ICs for VI management can be terminated when protective measures are no longer necessary to safeguard human health. This decision is data-driven and is based on assessments of current exposures and anticipated future exposures. Regardless of the exact scenario, modification of system operation or the selection of a curtailment strategy will depend on site-specific conditions and should be approached as a process based upon the use of MLE to evaluate and demonstrate effective operation of the VIMS and/or to provide justification that ongoing VIMS OM&M is no longer warranted. The OM&M plan should clearly define the closure criteria (i.e., cleanup levels for the vapor source) and provide guidance for phased decommissioning of the VIMS(s). MLE should be used to support decision-making, and some MLE may be more appropriate or applicable than others depending upon the site and regulatory conditions. For these reasons, the reader is encouraged to refer to the **Multiple Lines of Evidence Fact Sheet**; the **Vapor Intrusion Mitigation System Operation, Maintenance, and Monitoring Fact Sheet**; and the **Conceptual Site Models for Vapor Intrusion Mitigation Fact Sheet** in addition to the **Vapor Intrusion Mitigation System Curtailment and Shutdown Fact Sheet**.

The following ITRC technology information and fact sheets discuss considerations applicable for the VI mitigation phase of a project (see **https://itrcweb.org/vapor-intrusion-toolkit**):

- Design and Implementation Considerations for Vapor Intrusion Mitigation Approaches Fact Sheet
- Vapor Intrusion Mitigation System Construction Quality Assurance Fact Sheet
- Vapor Intrusion Mitigation System Curtailment and Shutdown Fact Sheet
- Vapor Intrusion Mitigation System Operation, Maintenance, and Monitoring Fact Sheet
- Vapor Intrusion Remediation and Institutional Controls Fact Sheet

Remediation/VIMS needs may be reevaluated at any stage due to changing data, property use, or anticipated future uses. Updated information should regularly be integrated into the CSM and site-specific CEP, potentially modifying closure strategies and/or the attainment criteria according to new site conditions. For more details see **Chapter 3: Community Engagement** and **Chapter 10: Vapor Intrusion Mitigation**.

Long-term VI mitigation can be achieved using a managed closure strategy that incorporates long-term OM&M and/or ICs that remain until either the VI pathway is eliminated and/or detected concentrations are reduced to below applicable target levels, at which point restrictions on land or building use are no longer justified (see **Section 11.5 Managed Vapor Intrusion Closure**). In other instances, the data may demonstrate that the VIMS is no longer necessary and monitoring requirements can be eliminated entirely, resulting in unrestricted closure with respect to VI (see **Section 11.6 Vapor Intrusion Closure**).

11.5. Managed Vapor Intrusion Closure

The ideal exit strategy results in termination of all monitoring, remedial activities, and ICs; however, it may not be feasible to remediate or mitigate to completely eliminate VFCs or the VI pathway for a site or building. A managed VI closure of a site refers to the completion of a VI project under some form of long-term restrictions. Benchmarks or criteria in which managed VI closure may be achieved are generally related to current and future site/land use and jurisdictional oversight authority. Managed VI closure strategies aim to achieve regulatory closure (jurisdictionally defined) while the need for VI mitigation (e.g., VIMS, building modifications), ongoing monitoring and reporting, and/or ICs are required to protect current and/or future building receptors. A managed VI closure could be implemented as either an intermittent or long-term strategy (e.g., ICs, deed restrictions, permanent building modifications, etc.) to

eliminate (or mitigate to the extent feasible such that associated risk is also managed) the VI pathway indefinitely, requiring adhering to property restrictions and/or implementing long-term OM&M plans, stakeholder management, or CEPs.

Managed VI closure strategies may include ICs, VIMS, or permanent building modifications to successfully address a complete VI pathway or a VI pathway that is currently incomplete but may become complete under future use of the property or change in building conditions (e.g., new penetrations in the slab, new cracks, different HVAC system operations). The determination to implement a managed VI closure strategy can be made at any stage of the project life cycle. At the conclusion of each VI project stage, the VI project team should use an MLE approach and determine whether the VI pathway is incomplete or complete and determine the risk to current and future building receptors. It is possible to apply a conclusion to the entirety to the site, a portion of the site, or a building. **Figure 11-1** and **Figure 11-2** depict the typical VI project stages and MLE collected at each stage that support the decision to either continue the VI project on to the next stage or conclude the VI project.

Managed VI closure of a site, portion of a site, or building should consider the following issues:

- Are chemical concentrations detected greater than site-specific remediation/mitigation goals, resulting in potential risks to human health?
- Is a mitigation measure needed to achieve no significant human health risks for current or future building receptors?
- If VIMS is in operation, what OM&M requirements are needed for building occupancy (current or future)?
- Is ongoing land management needed?
- Should the property use be restricted (i.e., nonresidential use)?
- Which stakeholder, entity, or agency will be responsible for ongoing management of ICs and/or VIMS OM&Ms?
- Do the data collected from the site indicate no VI risk to current building occupants but do indicate the potential for a VI risk to future building occupants if building modifications are made?

For a site, portion of a site, or building where source remedies and/or mitigation did not eliminate the VI pathway and detected concentrations remain greater than the applicable building receptor scenario, it can be concluded the VI pathway is complete and there may be a potential risk to current or future building receptors. As a result, the management of the complete VI pathway will need to be performed long-term to ensure ongoing protectiveness of building receptors. This can be achieved using a managed closeout strategy that incorporates long-term OM&M and/or ICs that remain until either the VI pathway is eliminated and/or detected concentrations are reduced to below applicable target levels and there is no potential future pathway; at that point, restrictions on land or building use are no longer justified.

ICs are a form of LUCs that provide protection from exposure to contaminants on a site. ICs consist of administrative or legal restrictions on a site, but LUCs can also use physical measures, such as ECs (e.g., typical mitigation measures, physical barriers). In contrast to ECs, ICs are primarily government controls, proprietary controls (e.g., deed restrictions), enforcement or permit mechanisms, and informational devices. Planning that protects human health and the environment and uses all aspects of an IC life cycle is essential for long-term success (e.g., a long-term stewardship plan). As it relates to the VI pathway, ICs can be applied as a stand-alone remedy (for undeveloped lands or restricted use on developed land), as part of an overall remedy selection, or as a mechanism that requires ongoing VIMS OM&M. More details are provided in the accompanying **Vapor Intrusion Remediation and Institutional Controls Fact Sheet** and **Institutional Controls Technology Information Sheet**.

The following ITRC technology information and fact sheets discuss considerations applicable for a managed VI closure strategy (see **https://itrcweb.org/vapor-intrusion-toolkit**):

- Design and Implementation Considerations for Vapor Intrusion Mitigation Approaches Fact Sheet
- Institutional Controls Technology Information Sheet
- Vapor Intrusion Mitigation System Curtailment and Shutdown Fact Sheet
- Vapor Intrusion Remediation and Institutional Controls Fact Sheet

For further information on the various types of ICs, also refer to ITRC's *Long-term Contaminant Management Using Institutional Controls* (ITRC 2016).

The acceptance of managed VI closure strategies may vary from jurisdiction to jurisdiction; it is best practice to engage with the regulatory agency early in the VI project to understand what is required for VI closure. Informed decision-making relies on an up-to-date and accurate CSM, which is essential for ensuring the success of environmental site management efforts. A review of the comprehensive CSM at the end of each VI project stage should be conducted and discussed with the applicable regulatory agency before determining conclusions. For more information see **Chapter 4: Conceptual Site Model**.

11.6. Vapor Intrusion Closure

For a site, portion of a site, or building where VI source remediation/removal eliminates VFCs in concentrations above the applicable screening levels, it can be concluded there is no complete VI pathway or future potentially complete VI pathway; therefore, it can be considered for unrestricted VI closure. *Unrestricted* refers only to the VI component at a site. This section focuses on the closure of the VI pathway, which may be only one component of a site. Overall site closure should consider all contaminated media and be discussed with the applicable regulatory agency before reaching conclusions. Furthermore, under some state and federal jurisdictions (i.e., DOD), the transfer of property may not occur until state and federal concurrence that unrestricted use / unrestricted exposure is achieved for the overall site; best practice is to engage with the applicable regulatory agency. This contrasts with a managed VI closure discussed in **Section 11.5** where the completion of a VI project required some form of long-term restrictions for current and/or future buildings.

The goal of VI project closure is to eliminate all potential current and future complete VI pathways for a site such that VFCs are below applicable levels and no mitigation measures or ICs are required to protect current or future building receptors. OM&M and ICs for VI management can be terminated when protective measures are no longer necessary to safeguard human health. This decision is data-driven and based on assessments of current exposures and anticipated future exposures. The OM&M plan should clearly define the VI closure criteria (i.e., cleanup levels for the vapor source) and provide guidance for phased decommissioning of the mitigation system(s). For further information see **Section 10.6** and the corresponding **Vapor Intrusion Mitigation System Curtailment and Shutdown Fact Sheet**.

Regardless of the exact scenario, modification of system operation or the selection of a curtailment strategy will depend on building and site-specific conditions and should be approached as a process based upon the use of MLE to evaluate and demonstrate effective operation of the VIMS and/or to provide justification that ongoing VIMS OM&M is no longer warranted. The OM&M plan should clearly define the VI closure criteria (i.e., cleanup levels for the vapor source) and provide guidance for phased decommissioning of the VIMS. MLE should be used to support decision-making, and some MLE may be more appropriate or applicable than others depending upon the building, site and regulatory conditions. For these reasons, the reader is encouraged to refer to the **Multiple Lines of Evidence Fact Sheet**, the **Vapor Intrusion Mitigation System Operation, Maintenance, and Monitoring Fact Sheet**, and the

Conceptual Site Models for Vapor Intrusion Mitigation Fact Sheet in addition to the Vapor Intrusion Mitigation System Curtailment and Shutdown Fact Sheet.

VI mitigation curtailment approval, the ability and authority to remove an IC, and VI closure strategy acceptance may vary from jurisdiction to jurisdiction. It is best practice to engage with regulatory agency early in the project to understand what is required for VI closure. Stakeholder notifications should be made to the appropriate regulatory agencies and private entities that VI closure criteria have been met and that OM&M and/or the ICs have been or can be discontinued (see the Vapor Intrusion Remediation and Institutional Controls Fact Sheet).

The possible routes to VI closure should be considered starting at the beginning with the preliminary VI exposure assessment and reassessed throughout the investigation, evaluation, and mitigation phases, as applicable. It may be possible to achieve VI closure for the VI component for a VI project and still need to address other media that are outside the scope of this document. Unrestricted VI closure is an exit strategy that allows for the termination of all monitoring, remedial activities, VI mitigation, and ICs resulting from the elimination of the VI component at the site.

This portion of the page left blank intentionally. Acknowledgments begin on the following page.

ACKNOWLEDGMENTS

Products like the Interstate Technology & Regulatory Council's (ITRC) Vapor Intrusion Toolkit are only possible thanks to the contributions of many dedicated individuals, including those who came before us. Their hard work and commitment have made the ITRC vapor intrusion documents and training courses one of the leading resources for staff seeking guidance on vapor intrusion issues.

The Team Leaders (TLs) and Program Advisors (PAs) for the Vapor Intrusion Update Team included:

- Debra Thoma (TL), South Carolina Department of Health & Environmental Control
- Tina Ures (TL), California State Water Resources Control Board
- Matthew Williams (TL), Michigan Department of Environment, Great Lakes, and Energy
- Bobbilynne Koepke (PA), Environmental Works, Inc.
- Susan Cummins (PA), Environmental Works, Inc.

Thank you to all the Subgroup Leaders and other key team members. Without their hard work and dedication to completing this project, this document would not have been possible.

- Rafat Abbasi, Geosyntec Consultants, Inc.
- Lila Beckley, GSI Environmental, Inc.
- Ashley Blauvelt, Rhode Island Department of Environmental Management
- Jennifer Borski, Wisconsin Department of Natural Resources
- Angus Chan, California State Water Resources Control Board
- Corin Fogle, Ohio Environmental Protection Agency
- David Folkes, Geosyntec Consultants, Inc.
- Tom Fox, Colorado Division of Oil and Public Safety
- Theresa Gabris, GTA
- Richard Hamner, Alabama Department of Environmental Management
- Ian Hers, Hers Environmental Consulting, Inc.
- Chase Holton, GSI
- Matthew Jenny, GSI
- Kelly Johnson, Jacobs
- Maya Key, Kennedy/Jenks

- Jane Parkin Kullmann, Woodard & Curran
- Matthew Lahvis, Shell
- Andrew Leavitt, California Department of Toxic Substances Control
- Diana Marquez, Burns & McDonnell Engineering Company, Inc.
- Susan McKinley, Indiana Department of Environmental Management
- Benjamin Moan, Nevada Division of Environmental Protection
- Catherine Regan, Haley & Aldrich
- Andrew Rodak, TRC Companies
- Lenny Siegel, Center for Public Environmental Oversight
- Jennifer Stackhouse, California Department of Toxic Substances Control
- Laura Trozzolo, TRC Companies

A special note of thanks to ITRC and its Board of Advisors for supporting this team since its inception in 2004. The support, staff time, expertise, assistance, and resources that ITRC has provided were instrumental for these documents and the completion of the latest version. In addition, as this document draws on the foundation of previous guidance documents, ITRC would like to thank the past TLs and other team members.

Technical Resources for Vapor Intrusion Mitigation—December 2020

- Kelly Johnson (TL), North Carolina Department of Environmental Quality
- Matthew Williams (TL), Michigan Department of Environment, Great Lakes, and Energy
- Steve Brauner (PA), Environmental Works, Inc.
- Bobbilynne Koepke (PA), Environmental Works, Inc.

Petroleum Vapor Intrusion: Fundamentals of Screening, Investigation, and Management—October 2014

- John Boyer (TL), New Jersey Department of Environmental Protection
- John Menatti (TL), Utah Department of Environmental Quality
- Matthew Williams (TL Training Team), Michigan Department of Environmental Quality
- Mary Yelken (PA), The Yelken Group

Vapor Intrusion Pathway: A Practical Guideline—January 2007

- John Boyer (TL), New Jersey Department of Environmental Protection

- Bill Morris (TL), Kansas Department of Health and Environment
- Steve Hill (PA), RegTech, Inc.

ITRC Vapor Intrusion Team Members

Key: ○ – Team Member ● - Team or Subgroup Leader

Name	Company	2007	2014	2020	2026
Aarons, Gerard (Jerry)	California Environmental Protection Agency, California Department of Toxic Substances Control				○
Abbasi, Rafat	Geosyntec Consultants, Inc.				○
Abraham, Mayble	EHS Support, LLC				○
Abrera, Bianca	TRC				○
Adsetts, Kit	Cardno			○	
Alejo, Leah	U.S. Naval Facilities Engineering Service Center	○			
Alexander, Delonda	North Carolina Department of Environment and Natural Resources	○	○		
Alger, Christopher	Terraphase				○
Allan, Jane	Apex Companies, LLC			○	
Allred, Shyla	AECOM				○
Almcrantz, Jason	U.S. Department of Energy			○	
Amodeo, Kristen	ERM				○
Anderson, Harry	W.L. Gore & Associates, Inc.	○			
Ansari, Mahta	Washington ECY				○
Anstaett, Ashley	Burns & McDonnell Engineering Company, Inc.				○
Anthony, Rich	Weston Solutions				○
Arzate, Lety	City of San Antonio			○	
Aufderhaar, Eric	North Carolina Department of Environmental Quality			○	
Badalamenti, Laura	Michigan Department of Environment, Great Lakes, and Energy			○	
Baiden, Eric	Utah Department of Environmental Quality			○	
Bailey, Sam	Kleinfelder				○
Barker, Nicholas	TRC				○
Barnett, Pam	RACER Trust				○
Bator, Susan	GZA GeoEnvironmental, Inc.			○	
Bauders, Vanessa	U.S. Army Corps of Engineers	○			
Bauman, Bruce	American Petroleum Institute		○		
Baushke, Sam	Geosyntec Consultants, Inc.			○	
Bays, Erica	Michigan Department of Environment, Great Lakes, and Energy			○	
Beckley, Lila	GSI Environmental, Inc.		○	●	●
Bennett, David	GES, Inc.		○		○
Bergeron, Eric	Golder Associates			○	
Berry, Jody	Wood PLC			○	
Biksey, Tom	Environmental Strategies Consulting, LLC	○			
Blauvelt, Ashley	Rhode Island Department of Environmental Management				●
Blessing, Todd	Alaska Department of Environmental Conservation		○	○	○
Blodgett, Eric	Barr Environmental Company		○	●	
Bolint, James	GHD			○	
Bond, Bob	Langan				○
Bonniwell, Everett	Protect Environmental			○	

Name	Company	2007	2014	2020	2026
Booze, Thomas	California Environmental Protection Agency, California Department of Toxic Substances Control		○		
Borski, Jennifer	Wisconsin Department of Natural Resources			●	●
Boyer, John	New Jersey Department of Environmental Protection (2007, 2014); Geosyntec Consultants (2020); Emeritus (2026)	●	●	●	●
Brewster, Michaela	Terracon			○	
Briley, Siona	New Mexico Environmental Department				○
Brodock, Keith	Integral Consulting			●	
Broughton, Anita	Haley & Aldrich, Inc.	○			
Brown, Andre	W.L. Gore & Associates, Inc.	○			
Brown, Christopher	Delaware Department of Natural Resources and Environmental Control		●		
Brown, Kevin	San Francisco Bay Regional Water Quality Control Board		○		
Brown, Marshall	South Dakota Department of Environment and Natural Resources			○	
Brown, Michelle	U.S. Air Force			○	
Brown, Sarah	North Carolina Department of Environmental Quality				○
Bulbulkaya, Ahmet	Tennessee Department of Environment and Conservation, Conservation, Environment				○
Burk, Tonia	Georgia Environmental Protection Division	○			
Burns, Richard	Conestoga Associates (2007); Conestoga-Rovers & Associates (2014)	○	○		
Burrows, Chris	ERM			○	
Buzgo, Christopher	Ramboll			○	
Byrd, Stacy	CETCO				○
Caldwell, Donna	U.S. Navy		○	○	
Caldwell, Kimberly	Department of Environmental Conservation Waste Management & Prevention Division			○	○
Camarata, Mary	Oregon Department of Environmental Quality	○			
Camera, Frank	New Jersey Department of Environmental Protection		○		
Capasso, J.R.	City of Trenton, New Jersey		●		
Carey, Brian	Terracon			○	
Carrington, Troy	Shell			○	
Cezar, Norlito	Parsons Corporation			○	
Chacon, Michael	Pueblo de San Ildefonso		○		
Champagne, Jared	Louisiana Department of Environmental Quality			○	
Chan, Angus	California State Water Resources Control Board				●
Chance, Joel	GHD			○	
Chang, Pamela	Battelle Memorial Institute			○	
Chapman, William	Virginia Department of Environmental Quality		○		
Chappel, Carlyn	R2			○	
Chiger, Mariya	Delaware Department of Natural Resources and Environmental Control				○
Chilcote, Laurie	Cox-Colvin				○
Christodoulatos, Eric	Honeywell			○	
Ciblak, Ali	Geosyntec Consultants, Inc.			○	
Cohen, Matthew	California State Water Resources Control Board			○	
Coley, James	South Australian Environmental Protection Agency			○	
Colmer, James	BB&E, LLC		○		

Name	Company	2007	2014	2020	2026
Cook, Anna-Marie	U.S. Environmental Protection Agency			○	
Cook, Laura	U.S. Navy				○
Cook, Shannon	Ohio Environmental Protection Agency			●	
Corcoran, Andrew	ERM			○	
Cordano, Dayna	California State Water Resources Control Board			○	○
Corsello, Joe	Sanborn Head & Associates, Inc.			●	
Cox, Craig	Cox-Colvin			○	○
Cox, Douglas	Mitretek Systems	○			
Crum, Jeff	Hamp, Mathews & Associates, Inc.			○	○
Cushing, Pamela	Canada Department of National Defence			○	
Dally, Katie	Arcadis			○	
Davin, Jeffrey	Brown and Caldwell				○
Davis, Luke	Tetra Tech, Inc.			○	
Davis, Robin	Utah Department of Environmental Quality		●		
Denly, Elizabeth	TRC				○
DeVaull, George	Shell		●	○	○
Donatucci, John	Kleinfelder				○
Dorrington, Terri	Montana Department of Environmental Quality				○
Dubec, Katie	AECOM				○
Dukes, Craig	South Carolina Department of Health and Environmental Control	○			
Dyson, Joann	GHD				○
Easly, Dianne	U.S. Environmental Protection Agency	○			
Ecker, Paul	EES Environmental Consulting, Inc.			○	
Edwards, Amy	Holland & Knight, LLP	○			
Egli, Matthew	New York State Department of Environmental Conservation				○
Eichberger, Jay	Michigan Department of Environment, Great Lakes, and Energy			●	○
Eiken, Tim	Missouri Department of Natural Resources			○	○
Eklund, Bart	URS Corporation	○	○		
Elcoate, Will	Alpha Analytical		○		
Epema, David	Missouri Department of Natural Resources			○	
Epple, Eric	Arcadis				○
Eremita, Peter	Maine Department of Environmental Protection	○			
Ettinger, Robert	Geosyntec Consultants, Inc.		○		○
Farnum, Rachel	GE Global Research	○			
Faulkner, Scott	Jacobs				○
Felix, Mike	U.S. Army Corps of Engineers				○
Ferguson, Chris	Protect Environmental			○	
Ferreira, James	U.S. Environmental Protection Agency			○	
Fiedler, Becky	Illinois Environmental Protection Agency			○	
Fields, Cheryl	Connecticut Department of Energy and Environmental Protection				○
Fisher, Mark	U.S. Army Corps of Engineers	○			
Fitch, Todd	U.S. Air Force Civil Engineer Center			○	
Fitton, Douglas	LFR Inc.	○			
Flagg, Jason	Langan			○	
Flammia, Dwight	Virginia Department of Health				○
Fogle, Corin	Ohio Environmental Protection Agency				●
Folkes, David	EnviroGroup Limited (2007); Geosyntec Consultants, Inc. (2014, 2020, 2026)	●	●	●	●

Name	Company	2007	2014	2020	2026
Foran, Sarah	Utah Department of Environmental Quality			○	
Fox, Tom	Colorado Department of Labor and Employment, Division of Oil and Public Safety			○	●
Frey, Noah	TRC			○	
Friedrich, Aaron	ERM			○	○
Futrell, Andrea	Support and guidance in the preparation of this document	○			
Gabris, Theresa	GTA				●
Galloway, Richard	Delaware Department of Natural Resources and Environmental Control	○		○	
Garrett, Valerie	Missouri Department of Natural Resources		○		
Gates, Ellyn	U.S. Environmental Protection Agency				○
Gates, Kimberly	U.S. Naval Facilities Engineering Service Center	○			
Gath, Ken	California Environmental Protection Agency, California Department of Toxic Substances Control			○	
Gattenby, Jessica	Arcadis				○
Gaurin, Sandra	BEM Systems, Inc. (2007); Tetra Tech (2014)	○	○		
Geissler, Jared	Terracon				○
Gilland, Ken	Buck Engineering	○			
Gillespie, Rick	Regenesis			●	
Gimson, Kirby	Intrinsyx				○
Gledhill, Johnathan	Policy Navigation Group	○			
Golding, Joshua	Langan			○	
Goodwin, Debi	Arizona Department of Environmental Quality				○
Gorman, Angela	South Carolina Department of Health and Environmental Control			●	
Grant, Jamie	Alaska Department of Environmental Conservation			○	
Grant, Peter	EPRO			●	○
Grape, Tim	Minnesota Pollution Control Agency			●	
Graves, Cheryl	Arizona Department of Environmental Quality				○
Green, Scott	Arizona Department of Environmental Quality			○	
Grevengoed, Lincoln	Utah Department of Environmental Quality				○
Grimes, Jerry	Virginia Department of Environmental Quality	○			
Groves, Matthew	GHD			○	
Gruszczak, Carl	Connecticut Department of Energy & Environmental Protection			○	○
Guinot, Guy	ERM			○	
Guiseppi-Elie, Annette	DuPont Engineering	○			
Haborak, Nikki	Georgia Environmental Protection Division			○	
Haddad, Elie	Haley & Aldrich, Inc.			○	
Hajicek, Marilyn	Colorado Department of Labor and Employment	○			
Hale, Kevin	New York State Department of Environmental Conservation		○		
Hamilton, Megan	Arcadis				○
Hamner, Richard	Alabama Department of Environmental Management				●
Hanley, David	Wood PLC (2020); Hanley Environmental (2026)			○	○
Hanley, Jeanene	Arizona Department of Environmental Quality	○			
Harrington, Jim	New York Department of Environmental Conservation	○			
Harrover, Poppy	U.S. Army			○	

Name	Company	2007	2014	2020	2026
Hartman, Blayne	H&P Mobile Geochemistry (2007); Hartman Environmental Geoscience (2014)	●	●		
Haseltine, Michael	North Carolina Department of Environmental Quality				○
Hatton, Thomas	Clean Vapor LLC			○	
Hawbaker, Carol	Illinois Environmental Protection Agency				○
Hawkins, Dusty	Alabama Department of Environmental Management				○
Hawthorne, Mike	GEI Consultants, Inc.			○	
Hecker, Brian	GES, Inc.			○	
Hecker, Joel	Pioneer Technologies Corporation			○	
Heckle, Chris	Protect Environmental			○	
Heidlauf, David	Ramboll			○	
Henry, Christophe	Jacobs				○
Hernandez, Noel	New Mexico Environmental Department				○
Hers, Ian	Golder Associates Ltd (2014); Hers Environmental Consulting, Inc. (2020, 2026)		●	○	●
Hewitt, Geoff	ION Science, Inc.		○		
Higgins, Tom	Minnesota Pollution Control Agency	○	○		
Hodny, Jay	W.L. Gore & Associates, Inc. (2007); Amplified Geochemical Imaging, LLC (2014)	○	○		
Hoffine, Stephen	Burns and McDonnell Engineering Company, Inc.	○			
Holton, Chase	GSI Environmental, Inc.				●
Holyoak, Avery	Utah Department of Environmental Quality			○	
Hong Luo, Emma	Chevron			○	○
Hopkins, Harley	American Petroleum Institute (2007); ExxonMobil (2014)	○	○		
Hornaday, Chuck	Vadose Remediation Technologies			○	
Horwath, Andrew	Civil & Environmental Consultants, Inc.			○	
Hoylman, Kyle	Protect Environmental			○	
Huber, Jane	Eurofins			○	
Hudgins, Mike	Terracon			○	○
Hutchens, James	Ramboll			○	○
Hutchinson, Courtney	Terracon				○
Hyman, Michael	North Carolina State University		○		
Ingling, Madison	Terraphase				○
Jaimes, Ricardo	Michigan Department of Environment, Great Lakes, and Energy			○	
Jarrett, Alex	Tetra Tech, Inc.			○	
Jeng, Chawn	California Environmental Protection Agency, California Department of Toxic Substances Control				○
Jenkins, Allison	Texas Commission of Environmental Quality				○
Jenny, Matthew	GSI Environmental, Inc.				●
Johnson, Greg	Colorado Department of Labor and Employment	○			
Johnson, Kelly	North Carolina Department of Environmental Quality (2020); Jacobs (2026)			●	●
Johnson, Undine	Georgia Environmental Protection Division		○		
Jones, Allan	Utah Department of Environmental Quality	○			
Jones, Ryan	Brown and Caldwell				○
Jonker, Sarah	Arcadis				○
Jordan, Brian	OSD				○
Justham, Tanya	New Hampshire Department of Environmental Services				○

Name	Company	2007	2014	2020	2026
Kallini, Kevin	TRC			○	
Kassel, Christopher	Arcadis			○	
Kavvadias, Eleni	U.S. Environmental Protection Agency			○	
Kelley, Haley	Alabama Department of Environmental Management			○	
Kemp, Hollyn	Virginia Department of Environmental Quality				○
Keshava, Udaya	Arcadis			○	
Key, Maya	Kennedy/Jenks				○
Kielbania, Daniel	AECOM				○
Kim, Agatha	TRC			○	
Kingsbury, Brandon	Montana Department of Environmental Quality			○	
Kinkade, Flint	Viridian Environmental Field Services		○		
Kistner, Brian	Burns & McDonnell Engineering Company, Inc.			○	
Klaybor, Jacob	U.S. Department of Transportation				○
Kolhatkar, Ravi	Chevron		○		
Kothur, Bheem	Florida Department of Environmental Protection	○			
Kram, Mark	Groundswell Technologies, LLC				○
Krasnecky, Nicholas	Terraphase				○
Kuhn, Kimberly	South Carolina Department of Health and Environmental Control			○	
Kunukcu, Yasemin	WSP				○
Kuzmkowski, Christine	Woodard & Curran			○	
KV White, Mary	Colorado Department of Labor and Employment, Division of Oil and Public Safety			○	
Kwiecinski, Michael	Colorado Division of Oil and Public Safety		○		
Kyrias, Matt	BBJ Group				○
Lahvis, Matthew	Shell		●	●	●
Lai (Eric), Ying	City of Casey, Victoria, Australia			○	
LaMarre, Ted	Hamp, Mathews & Associates, Inc.			○	
LaRosa, Steven	Weston & Sampson			○	
Lawrence, Bill	Idaho Department of Environmental Quality			○	
Lawson, Mike	U.S. Bureau of Reclamation			○	
Lay, Marsha	Indiana Department of Environmental Management			○	
Leavitt, Andrew	California Environmental Protection Agency, California Department of Toxic Substances Control				●
Lee, Alana	U.S. Environmental Protection Agency	○			○
Lee, Daniel	Arcadis			○	
Leeper, Mark	Colorado State University			○	
Lefticariu, Mihai	Missouri Department of Natural Resources			○	
Lesser, Ashley	Michigan Department of Environment, Great Lakes, and Energy				○
Levy, Laurent	Jacobs			●	○
Lewis, Kayla	Alabama Department of Environmental Management				○
Lewis, Nathan	Kentucky Division of Waste Management		○	●	○
Li, Hui	EKI Environment & Water, Inc.				○
Lindemann, Andrew	Geotech Environmental Equipment				○
Lingle, James	Electric Power Research Institute		○		
Liu, Jenny	DuPont Engineering	○			
Liu, Siwen	WSP				○
Lloyd, Diedre	Florida Department of Environmental Protection	○			
Locklin, Patricia	Maine Department of Environmental Protection		○		

Name	Company	2007	2014	2020	2026
Lofstrom, Dot	California Environmental Protection Agency, California Department of Toxic Substances Control		○		
Lopez Ortiz, Laura	Litoclean, S.L. (VAT nº: SB61993291)			○	
Lovenduski, Eric	Geosyntec Consultants, Inc.			○	○
Luis, Steve	Ramboll				○
Lund, Loren	CH2M Hill		●		
Lutes, Chris	Jacobs			○	○
Luther, Laura	Montana Department of Environmental Quality				○
MacDonald, Alexander	Regional Water Quality Control Board, Central Valley Region			○	
Madabhushi, Sriram	AECOM				○
Malagon, Alan	ERM			○	
Mallonee, Cathryn	Kansas Department of Health and Environment			○	
Mangum, Robert	Georgia Environmental Protection Division			○	
Marnicio, Ronald	Tetra Tech EC	○			
Marquardt, Shalom	Santa Clara County, CA				○
Marquez, Diana	Burns & McDonnell Engineering Company, Inc.	○	○	○	●
Martich, Ben	Geosyntec Consultants, Inc.		●		
Marzooghi, Solmaz	California State Water Resources Control Board			○	
Mathenia, Cheryl	Burns & McDonnell Engineering Company, Inc.				○
Mathews, Alan	Hamp, Mathews & Associates, Inc.			○	
Maude, Jennifer	Public Stakeholder				○
McAlary, Todd	Geosyntec Consultants, Inc.	●		○	
McClure, Mark	Kansas Department of Health and Environment			○	
McCoy, Richard	Air National Guard		○		
McCue, Dana	EHS Support, LLC				○
McDonnell, Erin	Oregon Department of Environmental Quality				○
McGill, Alicia	Georgia Environmental Protection Division			○	
McGraw, Maureen	Tetra Tech, Inc.			○	
McGuigan, Claire	Alberta Environment & Parks			○	
McHugh, Thomas	GSI Environmental, Inc.		○		
McIntosh, Lisa	Terraphase				○
McKercher, William	Mississippi Department of Environmental Quality	○	●		
McKinley, Susan	Indiana Department of Environmental Management			●	●
McLoughlin, Patrick	McLoughlin Environmental Science, LLC.				○
McNulty, Kathy	U.S. Department of Housing and Urban Development			○	
Meeuwsen, Melissa	Minnesota Pollution Control Agency			●	
Mehta-Sampath, Ameesha	U.S. Environmental Protection Agency			○	
Meier, Kari	OSD				○
Mellow, John	Pennsylvania Department of Environmental Protection	○			
Menatti, John	Utah Department of Environmental Quality		●		
Merola, Kristina	New Jersey Department of Environmental Protection				○
Meskanen, Nikki	GHD			○	
Metheny, Laura	Kansas Department of Health and Environment				○
Meyers, Alex	Integral				○
Michael, Sara	California Environmental Protection Agency, California Department of Toxic Substances Control			○	
Miller, Denise	Arcadis	○			
Millo, Alexander	TRC				○
Minor, Ricky	Alabama Department of Environmental Management			○	

Name	Company	2007	2014	2020	2026
Moan, Benjamin	Nevada Division of Environmental Protection				●
Monaghan, Pamela	Alabama Department of Environmental Management			○	
Monette, Stephanie	New Hampshire Department of Environmental Services				○
Mongeon, Robin	New Hampshire Department of Environmental Services	○			
Montero, Raymond	District Department of the Environment (Washington, DC)		○		
Morales, Evelina	Oklahoma Department of Environmental Quality	○			
Morris, Melinda	South Australian Environmental Protection Agency			○	
Morris, William	Kansas Department of Health and Environment (2007); Vapor Mitigation Sciences, LLC (2014, 2020)	●	●	●	
Morrison, Shane	Michigan Department of Environment, Great Lakes, and Energy				○
Mulry, Christopher	GES, Inc.		●		
Murshed, Nabil	Georgia Department of Natural Resources				○
Muthu, Ranga	ExxonMobil				○
Myers, Perry	California Environmental Protection Agency, California Department of Toxic Substances Control				○
Myller, Brian	Pinyon Environmental, Inc.			○	
Nagashima, Josh	State of Hawaii		●		
Nathan, Bailey,	Delaware Department of Natural Resources and Environmental Control				○
Navas, Sandra	EP Petroecuador			○	
Nemesh, Joseph	Tetra Tech, Inc.			○	
Newhart, Gary	U.S. Environmental Protection Agency			○	
Newton, Susan	Colorado Department of Public Health and Environment	○			
Ni'Mary, April	Virginia Department of Environmental Quality			○	
Nichols, Eric	LFR Inc. (2007); Substrata LLC (2014)	○	○		
Nicholson, Paul	Geosyntec Consultants, Inc.			○	○
Nightingale, Elizabeth	U.S. Environmental Protection Agency			○	○
Nilsen, Frannie	North Carolina Department of Environmental Quality				○
Nilsson, Jenny	Litoclean, S.L. (VAT nº: ESB61993291)			○	○
Noyes, Gerold	Vermont Department of Environmental Conservation		○		
O'Hearn, Michael	Wood PLC			○	
O'Neill, Harry	Beacon Environmental				○
Oliver, Rebecca	Geosyntec Consultants, Inc.			○	
Olm, Richard	Arizona Department of Environmental Quality	○			
Olson, Ethan	Battelle Memorial Institute			○	
Osgerby, Ian	U.S. Army Corps of Engineers	○			
Ostrowski, Marek	Brown and Caldwell			●	○
Pabich, Matthew	Idaho Department of Environmental Quality			○	
Paes Wilson, Fernanda	Fishbeck			○	
Paladugu, Srikanth	New Mexico Department of Health			○	
Panchol, Reuben	North Carolina Department of Environmental Quality			○	
Panzino, Paula	Arizona Department of Environmental Quality				○
Paolucci, Angela	Battelle Memorial Institute			○	
Pappoe, Michael	AECOM				○
Parcher, MaryAnn	Groundwater & Environmental Services, Inc.		○		

Name	Company	2007	2014	2020	2026
Parekh, Bhuvnesh	GZA GeoEnvironmental, Inc.			○	
Parkin Kullmann, Jane	Woodard & Curran				○
Patel-Coleman, Kanan	Burns & McDonnell Engineering Company, Inc.				○
Payne, Derek	Battelle Memorial Institute			○	
Penzone, Mike	Delaware Department of Natural Resources and Environmental Control				○
Peters, Daniele	EES Environmental Consulting, Inc.			○	○
Peterson, Chrissy	EHS Support, LLC				○
Petry, Augusto	ERM				○
Pettit, Michael	ERM				○
Pfister, Mike	California Environmental Protection Agency, California Department of Toxic Substances Control		○		
Pfister, Susan	Wood PLC			○	
Pica, Nasim	CDM Smith			○	
Pirozek, Crystal	New Jersey Department of Environmental Protection				○
Plantz, Gina	Newfields (2007); Haley & Aldrich, Inc. (2014, 2020, 2026)	○	○	○	○
Plath, Ryan	ERM				○
Poustchi, Ron	New Jersey Department of Environmental Protection		○	○	○
Puentes, Kenneth	Engineering Analytics, Inc.				○
Pulvino, Derek	U.S. Environmental Protection Agency				○
Rackow, Jeff	Arizona Department of Environmental Quality			○	
Rago, Richard	Haley & Aldrich, Inc.		●	○	
Ramacciotti, Francis	GHD				○
Regan, Catherine	Environmental Resource Management (ERM) (2014, 2020); Haley & Aldrich (2026)		●	●	●
Reinis, Sigrida	Langan			●	○
Reynolds, Krendon	Texas State University			○	
Rezendes, Andy	Alpha Analytical		●		
Rhiner, Ben	U.S. Navy				○
Rice, Will	Montrose				○
Rickli, Jonathan	Burns & McDonnell Engineering Company, Inc.				○
Riegert, Michael	U.S. Army Corps of Engineers			○	
Ries, Divinia	Elkhart County, Indiana				○
Ririe, Todd	BP		●		
Roberts, Steve	EES Environmental Consulting, Inc.				○
Robinson, Robert	TRC				○
Roche, Allison	Woodard & Curran			○	
Rodak, Andrew	Duncklee & Dunham, P.C. (2020); TRC (2026)			○	○
Rolison, Christopher	Pinyon Environmental, Inc.			○	
Roob, Christine	North Dakota Department of Environmental Quality			○	
Rosano, Debbie	U.S. Department of Energy			○	
Roth, Julia	Clean Vapor LLC			○	
Rousseau, Matthew	GHD				○
Rydquist, Eric	Brice				○
Saari, Rachel	Arcadis			○	○
Salameh, Marwan	Terracon			○	○
Sanchez, Craig	California State Water Resources Control Board			○	

Name	Company	2007	2014	2020	2026
Sandberg, Brian	GHD			○	
Sarmiento, Riz	California Environmental Protection Agency, California Department of Toxic Substances Control (2020); WSP (2026)			○	○
Schaettle, Jessica	Langan			○	
Schiwal, Alyssa	North Dakota Department of Environmental Quality				○
Schnorr, Barry	Ramboll				○
Schohn, Collin	BBJ Group				○
Schuver, Henry	U.S. Environmental Protection Agency	○			
Seitz, Sarah	Trihydro Corporation			○	
Shea, David	Sanborn, Head & Associates, Inc.			○	
Sherman, Jason	Air Force Environmental Law Field Support Center			○	
Siders, Mary	Nevada Division of Environmental Protection		○		
Siegel, Lenny	Center for Public Environmental Oversight	●		●	●
Singh, Deepak	District Department of the Environment (Washington, DC)		○	○	
Sirinek, Lawrence	West Virginia Department of Environmental Protection		○		
Smith, Matt	Orange County Sanitation District			○	
Smith, Nelly	Alabama Department of Environmental Management	○			
Sommargren, Erik	Sierra Club				○
Souza, Andre	Cetrel			○	
Specht, Megan	Pennsylvania Department of Environmental Protection				○
Spence, Lynn	Chevron		●		
Spencer, Tracey	U.S. Marine Corp			○	
Spiese, Richard	Vermont Waste Management Division			○	○
Sprenger, James	Jacobs				○
Stackhouse, Jennifer	Kleinfelder (2020); California Department of Toxic Substances Control (2026)			○	●
Stevens, Michael	TRC				○
Stocum, Jonathan	GES, Inc.			○	
Stokes, Kimberly	Jacobs				○
Strauss, Peter	PM Strauss and Associates	○			
Stubbs, Chris	Ramboll			○	○
Suggs, Shannon	North Dakota Department of Environmental Quality				○
Sun, Wenjie	Agency for Toxic Substances and Disease Registry				○
Szocinski, Thomas	GES, Inc.				○
Tanaka, John	BBJ Group				○
Taranto, Stephen	TRC			○	
Tay, Herman	WSP				○
Taylor, Neil	Utah Department of Environmental Quality	○			
Taylor, Zachary	National Park Service				○
Teipel, Alexa	Ramboll			○	
Telano, Jessica	Honeywell			○	
Teuscher, Kathleen	TRC				○
Thapa, Kritika	EA Engineering				○
Thoma, Debra	South Carolina Department of Health & Environmental Control		○	○	●
Thompson, Rod	Indiana Department of Environmental Management	○			

Name	Company	2007	2014	2020	2026
Thompson, Shannon	South Australian Environmental Protection Agency			○	
Thompson, Shannon	Trihydro Corporation		○		
Thornton, Garrett	California Environmental Protection Agency, California Department of Toxic Substances Control			○	
Tillman, Fred	U.S. Environmental Protection Agency	○			
Tisdell, Shawn	Alaska Department of Environmental Conservation				○
Tomlinson, Derek	Geosyntec Consultants, Inc.		○		
Tomlinson, Priscilla	Washington State Department of Ecology			○	
Traister, Matthew	O'Brien & Gere	○			
Trozzolo, Laura	AECOM (2014); TRC (2020)		○	○	○
Truesdale, Robert	RTI	○			
Tucker, Holly	Ohio Environmental Protection Agency			○	
Tull, Kerry	Wood PLC			○	
Ures, Tina	California State Water Resources Control Board				●
VanCleve, Audrey	Minnesota Pollution Control Agency		○		
Vandell, Terry	Phillips 66		○		
Varner, Abby	Hamp, Mathews & Associates, Inc.				○
Vedagiri, Usha	WSP				○
Verwiel, Ann	ToxStrategies, Inc.				○
Vowles, Cory	WSP				○
Wagaw, Wally	Michigan Department of Environment, Great Lakes, and Energy			○	
Waiss, Erik	Nebraska Department of Environment and Energy				○
Walker, Teresie	U.S. Naval Facilities Engineering Systems Command			○	
Walker, Tom	U.S. Environmental Protection Agency		○	○	
Walker, Yvonne	Navy Environmental Health Center	○			
Wallbom, Todd	California Environmental Protection Agency, California Department of Toxic Substances Control			○	
Wang, Nina	Alberta Health			○	
Wang, Qian	Georgia Department of Natural Resources				○
Wardle, Alexander	U.S. Environmental Protection Agency				○
Watikunas, Megan	Michigan Department of Environment, Great Lakes, and Energy				○
Weaver, Rachel	Terraphase				○
Weinberg, Nadine	ERM				○
Wells, Brett	U.S. Environmental Protection Agency			○	
Whetzel, Jim	W.L. Gore & Associates, Inc.(2007); Amplified Geochemical Imaging, LLC (2014)	○	○		
Willard, Frank	Virginia Department of Environmental Quality				○
Williams, Matt	Michigan Department of Environment, Great Lakes, and Energy	○	●	●	●
Williams, Matthew	Arcadis				○
Williamson, Bryce	New Mexico Environmental Department				○
Winger, Elizabeth	Eurofins			○	
Xavier, Garcia	Litoclean—Spain				○
Yang, Li	California Environmental Protection Agency, California Department of Toxic Substances Control			○	
Yargeau, Tedd	California Environmental Protection Agency, California Department of Toxic Substances Control		○		
Zemek, Peter	TRC				○

Name	Company	2007	2014	2020	2026
Zentmeyer, James	Civil & Environmental Consultants, Inc.			○	
Zevitas, Chris	U.S. Department of Transportation				○
Zhuang, Yuan	Ramboll				○
Ziegler, Ken	City of Albuquerque, Environmental Health Department			○	
Zimmerman, Brian	U.S. Department of Energy			○	
Zimmerman, John	U.S. Environmental Protection Agency				○

This portion of the page left blank intentionally. The Glossary begins on the following page.

GLOSSARY

Acute exposure: Exposure to elevated concentrations over a relatively short period of time.

Advection/advective flow: Bulk transport of the mass of discrete chemical or biological constituents by fluid flow within a receiving water. Advection describes the mass transport due to the velocity, or flow, of the water body. It is also defined as the process of transfer of fluids (vapors or liquid) through a geologic formation in response to a pressure gradient that may be caused by changes in barometric pressure, water table levels, wind fluctuations, or infiltration. It is transport of solute by the bulk motion of flowing groundwater.

Aerobic: Pertaining to, caused by, or characterized by the presence of oxygen.

Air dispersion modeling: The use of mathematical formulations to characterize air pollutant dispersion processes.

Air exchange rate (AER): The rate at which outdoor air enters a structure, exchanging with the indoor air.

Aliphatic: A hydrocarbon compound in which the carbon atoms are in a straight-chain, branched, or cyclic arrangement and are saturated or unsaturated.

Alkane: A group of chemicals (also known as paraffins or aliphatic hydrocarbons) for which the carbon atoms are all linked by single covalent bonds.

Alkene: A group of chemicals (also known as paraffins or aliphatic hydrocarbons) for which the carbon atoms contain at least one double bond.

Air sample: Collection of air taken from the surrounding environment (indoor or outdoor) to assess its composition. This type of sample typically measures the presence and concentration of pollutants, gases, particles, or other substances in the air. It is a critical tool for monitoring air quality, studying environmental conditions, and ensuring compliance with health and safety standards. These samples are often collected using specialized equipment.

Anaerobic: Pertaining to, caused by, or characterized by the absence of oxygen.

ANSI/AARST standards: National consensus practices used by federal and state agencies.

Aquifer: A body of permeable rock that can contain or transmit groundwater.

Aromatic: An organic compound that contains one or more benzene or equivalent heterocyclic rings.

Attenuation factor (AF): A ratio of the indoor air concentration to soil vapor or groundwater concentration; it is sometimes used to estimate the indoor air concentration from soil vapor or groundwater concentration.

Back drafting: The reverse flow of gas in the flues of fuel-fired appliances that results in the intrusion of combustion byproducts into the living space.

Background sources: Indoor or outdoor air concentrations of vapor-forming chemicals that are present in the absence of a release to the environment or in the absence of a complete vapor intrusion pathway.

Biodegradation: A process by which microorganisms transform or alter (through metabolic or enzymatic action) the structure of chemicals introduced into the environment (USEPA). The breakdown of chemicals by microorganisms.

Building envelope: The physical boundary between the conditioned and unconditioned environment of a structure, including the resistance to air and water transmission.

Building foundation: The base of the structure that is in direct contact with the ground. It provides structural support and provides stability. It can include concrete slabs, crawl spaces, basements, and various types of footings.

Building pressurization: The air pressure within a structure relative to the air pressure outside.

Capillary fringe / capillary zone: The pore spaces in soil just above the water table that may contain water above the static level from interactive forces between the water and soil.

Chemicals (or contaminants or constituents) of concern (COCs): Compounds derived from hazardous substances that are subject to evaluation for the purposes of applying risk-based corrective action decision-making. This is typically a smaller subset of chemicals from the list of chemicals of potential concern.

Chemicals (or contaminants or constituents) of potential concern (COPCs): Substances identified during environmental assessments as possibly posing risks to human health, ecosystems, or property, requiring further analysis to narrow down from a broad list to a "short list" of primary risk-driving chemicals.

Chlorinated vapor intrusion: Volatile chlorinated chemicals, typically originating from contaminated soil or groundwater, that migrate as vapors into overlying structures through cracks, gaps, or openings in the foundation.

Chronic exposure: Exposure to a low-level concentration over a long period of time.

C_{IA}: Measurements of vapor-forming chemical concentrations in indoor air.

Clean soil: Soil with an acceptable level of contamination that remains conducive to biodegradation of petroleum vapors.

Vapor intrusion closure/ unrestricted vapor intrusion closure: Closure due to the elimination of complete or potentially complete vapor intrusion pathways for a site such that vapor-forming chemicals are below applicable levels and no mitigation measures or institutional controls are required to protect current or future structure receptors.

Coal tar: A brown or black liquid of extremely high viscosity. Coal tar is one of the resultant byproducts when coal is carbonized to make coke or gasified to make coal gas. Coal tars are complex and variable mixtures of phenols, polycyclic aromatic hydrocarbons, and heterocyclic compounds. A byproduct of the pyrolysis of coal, coke, or oil in a closed vessel during the production of manufactured gas containing a small percentage of volatile organics and polycyclic aromatic hydrocarbons.

Community engagement: The process of communicating with local residents and other stakeholders to provide information throughout the investigation and cleanup of a contaminated site, providing opportunities for offering input about site investigation/cleanup plans, and facilitating the resolution of community issues related to a contaminated site.

Concentration gradient: The change of concentration over a certain distance.

Conceptual site model (CSM): (1) A three-dimensional representation of an environmental system and the biological, physical, and chemical processes that determine the transport and fate of contaminants through environmental media to environmental receptors and their most likely exposure modes. (2) A vapor intrusion CSM is a hypothesis about how contaminant releases occurred, the current state of the source zone, and current plume characteristics (plume stability). (3) A living collection of information about a site that considers factors such as environmental and land use plans, site-specific chemical and geologic conditions, and the regulatory environment. (4) An iterative representation of the site that summarizes and helps project planners visualize and understand available information. The vapor intrusion CSM is the primary planning and decision-making tool used to identify the key issues and the data necessary to transition a project from characterization through post-remedy. (5) Describes the potential chemical sources, release mechanisms, fate and transport pathways, impacted environmental media, receptors, and exposure pathways for current and reasonably anticipated future activities and land uses. This model documents current site conditions and serves to conceptualize the relationship among chemicals in environmental media, sources, and receptors through consideration of potential or actual migration and exposure pathways.

Conduit vapor intrusion preferential pathway (conduit VIPP): Conduit VIPPs are outside, or extend outside, of the building footprint and enhance transport toward the structure, such as sanitary sewers, utility tunnels or other pipes, and karst geology. These features essentially connect distal subsurface vapor-forming chemical sources to the structure itself. The vapor-forming chemical flux is through the interior of the conduit (see vapor intrusion preferential pathway).

Confining unit / aquitard: A layer of rock or soil of very low hydraulic conductivity that hampers the movement of groundwater in and out of an aquifer.

Construction quality assurance plan (CQA plan): A formal document outlining the processes, procedures, and activities required to ensure that a construction project meets specified quality standards. This plan typically includes guidelines for monitoring and testing materials, workmanship, and compliance with design specifications. It also identifies roles and responsibilities, inspection protocols, documentation requirements, and corrective action measures.

Coupon testing: A specimen of an installed material collected for testing or verification.

Cyclic: A compound that contains a closed ring of atoms.

Daughter products / degradation products: Substances formed when a chemical compound breaks down or undergoes a transformation due to physical, chemical, or biological processes. This breakdown can occur naturally (e.g., from sunlight, water, or microbial activity) or as a result of human activities.

Dense nonaqueous-phase liquid (DNAPL): A water-immiscible organic liquid that is denser than water (such as tetrachloroethene).

Depressurization: To remove the air pressure from.

D_{eff}: The effective diffusion coefficient of vadose-zone soil.

Diffusion: (1) Movement of vapors away from areas of higher concentration. (2) The process of net transport of solute molecules from a region of high concentration to a region of low concentration caused by their molecular motion in the absence of turbulent mixing.

Discharge criteria: Generic term used to describe emission regulatory limits.

Emergency response: Explosive conditions between the upper explosive limit and lower explosive limit that warrant mitigation by emergency responders.

Emission controls: Means employed to limit the discharge of gases.

Engineering controls (ECs): The methods or strategies that involve using technology or making physical changes to the structure or structure systems to reduce concentrations of vapor intrusion contaminants to acceptable levels or as low as practicable if still above acceptable long-term levels.

Expansion joints: An assembly designed to hold parts together while safely absorbing expansion and contraction.

Fick's law: The principle that diffusive flux goes from areas of high concentration to areas of lower concentration with a magnitude proportional to the concentration gradient.

Floor drain: A plumbing fixture that is installed in the floor of a structure designed to remove any standing water near it.

Flow velocity: Vector field that is used to describe fluid motion in a mathematical manner.

Flux: (1) Flow per unit area. (2) Rate of flow of fluid, particles, or energy through a given surface. (3) The mass (mass flux) or volume (flux) moving through an area per time.

French drain: A trench filled with gravel or rock or containing a perforated pipe that redirects surface water.

Gasolines: Petroleum mixtures characterized by a predominance of branched alkanes with carbon ranges from C3 to C12 and lesser amounts of aromatics, straight-chain alkanes, cycloalkanes, and alkenes of the same carbon range.

Heating, ventilation, and air conditioning (HVAC): The technology of indoor and vehicular environmental comfort, including heating, cooling, and air movement.

Heavy metal: A group of elements characterized by their high atomic weights, densities, or numbers. These metals include but are not limited to lead, mercury, cadmium, and chromium, and they possess distinctive properties such as toxicity and corrosion resistance.

Henry's Law: The principle that the amount of a gas dissolved at equilibrium in a certain quantity of liquid is proportional to the pressure of the gas in contact with the liquid.

Heterocyclic: A compound that contains a closed ring of atoms in which one of the ring members is not a carbon atom.

Human exposure pathway: Refers to the way a person can come into contact with a hazardous substance.

Indicator compound: A compound chosen for its likely presence in an area of interest that is used to estimate conditions as a whole for the area of interest.

Indoor air sample: A collection of air from within a structure or enclosed space to evaluate its quality and composition. These samples help identify the presence and concentration of contaminants such as vapor-forming chemicals or other pollutants. Indoor air sampling is crucial for assessing health risks, ensuring compliance with safety standards, and determining the effectiveness of air filtration or ventilation systems.

Inorganic compounds: Substance in which two or more chemical elements (usually other than carbon) are combined.

Institutional control (IC): A form of land use controls that provides protection from exposure to site-related contaminants.

Interior transport pathway: Enhanced airflow within a given structure.

Intrinsically safe: Lacking the energy necessary to cause ignition.

Johnson & Ettinger model (J&E model): A one-dimensional analytical solution to convective and diffusive vapor transport into indoor spaces. The model provides an estimated attenuation coefficient that relates the vapor concentration in the indoor space to the vapor concentration at the source of contamination.

Laser screed: A self-leveling head that is mounted on a telescopic boom used to smooth and level concrete.

Lateral inclusion zone / lateral screening distance: The zone of potential influence in which a source can impact surrounding receptors.

Light nonaqueous-phase liquid (LNAPL): A liquid that is not soluble and has a lower density than water.

Long-term stewardship: Activities implemented for the management of contaminated environmental media that are necessary to protect human health and the environment over time.

Lower explosive limit (LEL): The minimum concentration of a gas or vapor in the air that is capable of producing a flash or fire in the presence of an ignition source.

Managed vapor intrusion closure / restricted vapor intrusion closure: Strategies to achieve regulatory closure (jurisdictionally defined) while a need for a vapor intrusion mitigation system, structure modification(s), ongoing monitoring/ reporting, and/or institutional control remains.

Mass discharge: This is an integrated mass flux estimate (i.e., the sum of all mass flux measures across an entire plume); thus, it represents the total mass of any solute conveyed by groundwater through a defined plane. Mass discharge is therefore expressed as mass/time (e.g., g/d).

Mass flux: This is a rate measurement specific to a defined area, which is usually a subset of a plume cross section. Mass flux is thus expressed as mass/time/area (e.g., g•d-1•m-2).

Methanogenic: Able to produce methane from a limited number of substrates.

Middle distillates: Petroleum mixtures characterized by a wider variety of straight, branched, and cyclic alkanes, as well as polycyclic aromatic hydrocarbons and heterocyclic compounds with 372 carbon ranges of approximately C9 to C25.

Mitigation: Generally applied to actions that prevent or limit human exposure to vapor-forming chemicals.

Mitigation strategy: An approach used to reduce the severity of something, such as vapor intrusion.

Modeling: The use of computational tools and methods to simulate how chemical vapors, often from contaminated soil or groundwater, migrate into structures. These models help predict the behavior and concentration of hazardous vapors, such as chlorinated solvents or vapor-forming chemicals, as they travel through subsurface pathways like soil pores, cracks, or gaps in structure foundations.

Multiphase extraction (MPE): This is an environmental remediation technique used to remove contaminants from both soil and groundwater. This method is particularly effective for sites contaminated with petroleum hydrocarbons or chlorinated solvents. It involves the simultaneous extraction of multiple phases: the liquid phase (e.g., groundwater or free product like oil), the gas phase (e.g., volatile organic compounds in the air), and the solid phase (e.g., contaminants trapped in soil pores).

Natural draft: The use of natural atmospheric pressure to force gases of combustion out through a ventilation system.

Operation, maintenance, and monitoring (OM&M) plan: Refers to the routine inspection, servicing, and repairing or replacing of necessary equipment of an operating system.

Organic carbon partition coefficient: The theoretical ratio of the mass absorbed to soil particles versus the mass dissolved in pore water.

Organic vapor analysis: Tools that qualitatively measure organic vapors, such as a photoionization detector.

Outdoor air sample: A collection of air from the outdoor environment to assess its quality and composition. These samples are commonly used to monitor pollutants such as vapor-forming chemicals or other pollutants. They help evaluate the impact of natural and human activities on air quality, track regulatory compliance, and identify health or environmental risks.

Oxygen sink: A process (such as biodegradation) that reduces the amount of oxygen present.

Pathways: The process in which any chemical that can induce an adverse response may come in contact with receptors.

Perched aquifer: A water-saturated zone that is above or not directly connected to the regional aquifer; a perched aquifer may develop when saturated conditions are present above a low-permeability layer.

Petroleum industrial site / non-underground storage tank (UST) site: A source area where underground storage and aboveground storage tanks are not used.

Petroleum underground storage tank (UST) /aboveground storage tank (AST) site: A source area where underground storage and/or aboveground storage tanks are used.

Petroleum vapor intrusion (PVI): The process by which volatile hydrocarbons partition from petroleum-contaminated soils and/or groundwater and migrate through the vadose zone in gaseous form to receptors.

Phase partitioning: Separation of fuel into solid, liquid, and gas phases.

Phreatic (saturated) zone: The part of an aquifer, below the water table, in which all pores and fractures are essentially saturated with water.

Plenum: Continuous void space under the slab that can facilitate air circulation.

Post-installation verification: A testing procedure used to show that something is functioning properly after an initial installation or an upgrade.

Precluding factors: Elements that make a selected approach impossible by necessary consequence.

Preferential pathway: A generic, umbrella term encompassing both (1) natural and manmade features that enhance the migration of vapor-forming chemicals into a structure relative to migration through bulk soil and (2) general vapor entry points at the building envelope (e.g., foundation cracks, drains, expansion joints). In this document, we distinguish the features by referring to the former as conduit or vertical vapor intrusion preferential pathways and the latter as vapor entry points.

Preliminary conceptual site model (CSM): The first iterations of a conceptual site model used in the preliminary stages of site characterization.

Pressure field extension (PFE): An area beneath a concrete slab or foundation where a sufficient amount of negative pressure (vacuum) has been obtained.

Q_{BPC}: Airflow rates across a blower door associated with indoor air depressurization.

$Q_{building}$: The volumetric airflow of soil vapor within and out of a structure.

Q_{soil}: The volumetric airflow of soil vapor from the subsurface to indoor air.

Q_{SSG}: Measurements of vapor-forming chemical concentrations and airflow rates associated with sub-slab soil vapor depressurization.

Raoult's law: The principle that the vapor pressure of an ideal solution is directly dependent upon the vapor pressure of each chemical component and mole fraction of each component in the solution.

Rapid response / initial hazard abatement: An interim vapor intrusion mitigation approach that may be appropriate, under certain conditions (e.g., high contaminant concentrations and sensitive populations present), prior to implementing a long-term mitigation strategy for an occupied room or structure.

Reasonable maximum exposure (RME): the highest exposure that is reasonably expected to occur at a site, which in practice is estimated by combining upper bound (90–95 percentile) values for some but not all exposure parameters with the 95 percent upper confidence limit of the arithmetic mean for the chemical concentration.

Receptors: A vulnerable area of concern where members of the public or biologics could be exposed to toxic concentrations as the result of a release.

Redox potential: Chemical reduction-oxidation processes and conditions that can result in the alteration of a chemical compound.

Remediation/remedy: An action or set of actions that reduce the level of contamination or eliminate the source in the environmental medium (e.g., soil, groundwater) that is acting as the source of the vapor-forming chemicals in indoor air.

Residual fuels: Petroleum mixtures characterized by complex, polar polycyclic aromatic hydrocarbons and other high molecular weight hydrocarbon compounds with carbon ranges that generally fall between C24 and C40.

Response action: A specific activity or set of activities undertaken to investigate, assess, and ultimately address the potential or actual human exposure to hazardous chemical vapors that have migrated from a subsurface source (contaminated soil or groundwater) into the indoor air of structures.

Risk assessment: A series of analytical methods that characterize the probability, nature, and magnitude of risks to human health for various populations.

Risk communication: Actions, words, and other messages, responsive to the concerns and values of the information recipients, intended to help people make more informed decisions about threats to their health and safety. Risk communication is the formal and informal process of communication among and between regulatory agencies and organizations responsible for site assessment and management and the various parties who are potentially at risk from or are otherwise interested in the site.

Risk management: The process of deciding whether and how to manage risks to human health and the environment.

Sensitivity: A relative measure of the effect a model input parameter, such as soil porosity, soil moisture, or soil fraction of organic carbon, has on the model output, such as indoor air concentration or risk.

Site: The area(s) defined by the extent of migration of the vapor-forming chemicals, regardless of specific property boundaries.

Slab/structure slab: "Slab," in the context of vapor intrusion, is the structure/subsurface interface through which vapors can migrate.

Smoke pen: A handheld device that creates a puff or a trail of white smoke used to identify leaks or air flow direction.

Smoke testing / tracer gas testing: A nondestructive testing method that uses a nontoxic smoke or tracer gas to evaluate a system component.

Soil gas / soil vapor: The mixture of gases found in the small spaces (pores) between soil particles. These gases can originate from natural sources, such as microbial activity, or from human activities, like industrial spills or the use of underground storage tanks. Soil gas often includes components such as oxygen, carbon dioxide, nitrogen, methane, or vapor-forming chemicals.

Soil pore space: The air- or water-filled space that is between soil particles.

Soil vapor extraction (SVE): An environmental remediation technique used to remove volatile contaminants, like petroleum hydrocarbons or solvents, from soil. This method works by extracting vapors from the subsurface using wells or pipes installed in the contaminated area.

Sources: A location of the discharge of toxic substances and/or pollutants to environmental media.

Spatiotemporal: Having both spatial and temporal qualities.

Stack effect: Process in which warm air rises, causing negative pressure on a structure interior applied to the surface of the floor slab, resulting in a pressure differential that can exacerbate vapor intrusion.

Stakeholder: Affected tribal members, community members, members of environmental and community advocacy groups, and local governments.

Structure: On- or off-site residences; institutions (e.g., schools, hospitals); industrial, commercial, and office buildings; parks; or recreational areas inhabited or occupied by the public at any time without restriction and that are used for residential or industrial purposes on a regular basis.

Surrogates: Variables with a quantitative relationship to the target compound for a study sufficient to be useful as a substitute for directly measuring the target compounds.

Telemetry: Process of recording and transmitting the readings of an instrument.

Tortuosity: The ratio of the diffusivity in free space to the diffusivity in the porous medium.

Total petroleum hydrocarbons (TPHs): The sum total of all compounds composed of hydrogen and carbon in petroleum including all aliphatic and aromatic components.

Tracer: Substances that migrate similarly to the vapor-forming chemicals of interest for vapor intrusion.

Uncertainty: A model user's or site assessor's lack of knowledge of the true physical site parameters values, such as soil porosity, soil moisture, or soil fraction of organic carbon, that have an effect on the fate and transport of vapor-forming chemicals in the subsurface.

Upper explosive limit (UEL): The maximum concentration of a gas or vapor in the atmosphere that can ignite and cause a flash or fire in the presence of an ignition source.

Utilidor / utility tunnel / utility corridor: A passage used for routing utility lines, such as electric lines, water supply pipes, sewer pipes, and communications lines.

Vadose zone: The unsaturated zone of soil in which the pore space is filled with both air and water.

Vapor control technologies: Technologies employed to mitigate real or potential impacts from vapor intrusion.

Vapor entry point: Penetrations through the structure foundation such as cracks, expansion joints, and plumbing (e.g., defective plumbing or dry p-traps) that can enhance airflow through the foundation.

Vapor intrusion (VI): The process by which volatile vapors partition from contaminated groundwater or other subsurface sources and migrate upward through vadose-zone soils and into overlying structures.

Vapor intrusion component: The part of the overall site assessment or investigation that covers vapor-forming chemicals (VFCs) from a release, transport and migration of a complete or potentially complete pathway, and a current/future structure receptor. Sites with no current potential for subsurface VFCs or sites where subsurface VFCs are present but current or future complete pathways have been ruled out would not have a vapor intrusion component.

Vapor intrusion mitigation: A method, technology, control, or combination thereof used to prevent or reduce the severity of vapor intrusion.

Vapor intrusion mitigation system (VIMS): A group of interconnected parts or elements designed to prevent or reduce the severity of vapor intrusion specifically at a structure.

Vapor intrusion preferential pathway (VIPP): A pathway that intersects both the vapor source and the structure foundation and provides for an increased flow of vapors that is more than expected under typical conditions (i.e., a typical vapor transport through vadose-zone soils). Conduit VIPP and vertical VIPP are specific scenarios resulting in a vapor intrusion preferential pathway.

Vapor plume: The lateral and vertical extent of vapor-forming chemicals within the subsurface.

Vapor-forming chemicals (VFCs): Chemical compounds that readily volatilize to produce vapors.

Vent riser: Vertical exhaust piping connected to a horizontal vent system for passive or active mitigation.

Vent stack: A pipe placed vertically or nearly vertical for ventilation.

Vertical screening distance: The minimum distance in soil between a petroleum vapor source and structure foundation needed to effectively biodegrade hydrocarbons below a level of concern for petroleum vapor intrusion.

Vertical separation distance: The vertical distance from a petroleum vapor source to a structure foundation. The thickness of clean, biologically active soil between a contaminant mass and the lowest point of an overlying receptor.

Vertical vapor intrusion preferential pathway (vertical VIPP): Vertical VIPPs are within the structure footprint and generally enhance vertical transport into the structure that may not have happened under typical construction or operating conditions. Vertical VIPPs include features such as elevator sumps and dry wells (see vapor intrusion preferential pathway).

Volatile organic compounds (VOCs): A variety of chemicals, some of which may have short- and long-term adverse health effects, that are prone to evaporation at ambient temperatures.

This portion of the page left blank intentionally. Acronyms begin on the following page.

ACRONYMS

µg/L:	micrograms per liter
µg/m^3:	micrograms per cubic meter
1,1-DCE:	1,1-dichloroethene

A

ADE:	average daily exposure
AER:	air exchange rate
AF:	attenuation factor
AF_{gw}:	groundwater concentration attenuation factor
AF_{sg}:	soil gas concentration attenuation factor
AHU:	air handling unit
ALM:	asphalt latex membrane
APU:	air purifying unit
AST:	aboveground storage tank
ATD:	analytical thermal desorption
Atm-m^3 mol^{-1}:	one standard atmosphere per cubic meter per mole
AVMB:	aerobic vapor migration barrier

B

bgs:	below ground surface
BPC:	building pressure control
BTEX:	benzene, toluene, ethylbenzene, and xylenes

C

CAG:	community advisory group
cc:	cubic centimeter
CCAH:	Construction Code Applicable to Homes
CEP:	community engagement plan

CERCLA:	Comprehensive Environmental Response, Liability, and Accountability Act
CGI:	combustible gas indicator
CH_4:	methane
C/I:	commercial/industrial
CIA:	indoor air concentration
CIP:	community involvement plan
CM:	composite membrane
CO:	carbon monoxide
COC:	contaminant (or constituent or chemical) of concern
COPC:	contaminant (or chemicals) of potential concern
CPSi:	cancer potency slope, inhalation
CPT:	cone penetrometer testing
CQA:	construction quality assurance
CRDS:	cavity ring-down spectrometer
CSIA:	compound-specific isotope analysis
CSM:	conceptual site model
CSP:	concrete surface profile
CSV:	crawl-space ventilation
CTP:	communication test points
CVOC:	chlorinated volatile organic compound

D

DCA:	1,2-dichloroethane
DCE:	1,2-dichloroethylene
DCM:	dichloromethane
DELCD:	dry electrolytic conductivity detector
DNAPL:	dense nonaqueous-phase liquid
DQO:	data quality objective

E

EC:	engineering control
ECD:	electron-capture dissociation
EDB:	ethylene dibromide, also known as 1,2-dibromoethane
EDC:	ethylene dichloride, also known as 1,2-dichloroethane
EFC:	epoxy floor coating
EI:	environmental indicator
E&P:	oil exploration and production
EPC:	exposure point concentration
EPDM:	ethylene propylene diene monomer
ER:	exchange rate
ESA:	environmental site assessment
ESTCP:	Environmental Security Technology Certification Program
ETBE:	ethyl tert-butyl ether
eV:	electron volts
EVOH:	ethylene vinyl alcohol

F

FAQ:	frequently asked questions
FID:	flame ionization detector
ft:	feet
FTOH: f	luorotelomer alcohol

G

GAC:	granulated activated carbon
GC:	gas chromatography or gas chromatograph
GC/CRDS:	gas chromatograph / cavity ring-down spectrometer
GC/DELCD:	gas chromatograph / dry electrolytic conductivity detector
GC/ECD:	gas chromatograph / electron capture detector

GC/MS: gas chromatography / mass spectrometry

GW: groundwater

H

HASP: health and safety plan

HDPE: high-density polyethylene

Hg: mercury

HHRA: human health-risk assessment

HI: hazard index

HLC: Henry's Law coefficient

HQ: hazard quotient

HVAC: heating, ventilation, and air conditioning

HVS: high-volume soil vapor sampling

I

IA: indoor air

IC: institutional control

ID: inner diameter

ILCR: incremental lifetime cancer risk

in: inches

in-H_2O: 1 inch of water column

IRIS: Integrated Risk Information System

ITS: Indicator, Tracer, Surrogate program from the U.S. Environmental Protection Agency

IUR: inhalation unit risk

J

J&E: Johnson and Ettinger

L

L: liter

LADE: lifetime average daily exposure

LEL:	lower explosive limit
LFL:	lower flammability limit
LIF:	laser-induced fluorescence
LLDPE:	linear low-density polyethylene
L/min:	liter per minute
LNAPL:	light nonaqueous-phase liquid
LOE:	line of evidence
LOQ:	limit of quantitation
L_R:	diffusion reaction distance
L_T:	thickness of the soil layer
LUC:	land use control

M

MCLs:	maximum containment levels
MDL:	method detection limit
mg/L:	milligrams per liter
mg/m^3:	milligrams per cubic meter
MGP:	manufactured gas plant
Mil:	one-thousandth of an inch
MIP:	membrane interface probe
MLE:	multiple lines of evidence
mL/min:	milliliters per minute
mm Hg:	millimeter of mercury
MPE:	multiphase extraction
MS:	mass spectrometry
MSDS:	material safety data sheet
MTBE:	methyl tertiary-butyl ether
MUF:	modified uncertainty factor

N

NAPL:	nonaqueous-phase liquid
NCP:	National Oil and Hazardous Substances Pollution Contingency Plan
NM:	not measured or reported
NO_2:	nitrogen dioxide

O

O_2:	oxygen gas
OA:	outdoor air
OAT:	one-at-a-time
OD:	outside diameter
OM&M:	operation, maintenance, and monitoring
OVA:	organic vapor analyzer

P

Pa:	Pascal (unit)
PA:	Program Advisor
PADS:	passive adsorptive diffusion samplers
PAH:	polycyclic aromatic hydrocarbons
PCB:	polychlorinated biphenyls
PCE:	tetrachloroethene (also called perchloroethene and tetrachloroethylene)
PDB:	passive diffusion bag
PEEK:	tubing made from polyether ether ketone
PFAS:	per- and polyfluoroalkyl substances
PFCA:	perfluoroalkyl carboxylic acid
PFE:	pressure field extension
pg:	picogram
PHC:	petroleum hydrocarbon
PID:	photoionization detector

ppbv:	parts per billion by volume
ppm:	parts per million
ppmv:	parts per million by volume
PPRTV:	Provisional Peer Reviewed Toxicity Values
PQL:	practical quantitation limit
PRG:	preliminary remediation goals
PSSV:	passive sub-slab venting
PVC:	polyvinyl chloride
PVDF:	polyvinylidene
PVI:	petroleum vapor intrusion

Q

QA:	quality assurance
QAPP:	quality assurance project plan
QA/QC:	quality assurance/quality control
QC:	quality control

R

RAO:	remedial action objective
RCRA:	Resource Conservation and Recovery Act
RfC:	reference concentration
RfD:	reference dose
RfDi:	reference dose, inhalation
RH:	relative humidity
RL:	reporting limit
RME:	reasonable maximum exposures
ROD:	record of decision
ROI:	radius of influence
RP:	responsible party

RSL: Regional Screening Level

RTM: real-time monitoring

RVR: room ventilation rate

S

SAP: sampling and analysis plan

scfm: square cubic feet per minute

SDR: standard dimensional ratio

SIM: selective ion monitoring

SL: screening level

SMD: sub-membrane depressurization

SOP: standard operating procedure

SSAF: slab-specific attenuation factor

SSD: sub-slab depressurization

SSM: single-sheet membrane

SSP: sub-slab pressurization

SSV: sub-slab ventilation

SVE: soil vapor extraction

SVOC: semi-volatile organic compounds

T

TAME: tert-amyl methyl ether, an oxygenate

TBA: tert-butyl alcohol, an oxygenate

TCA: trichloroethane

TCE: trichloroethylene or trichloroethene

THQ: target hazard quotient

TL: Team Leader

TM: thermoplastic membrane

TPH: total petroleum hydrocarbons

TR:	target risk
T&R:	Turczynowicz and Robinson

U

UCL:	upper confidence limit
UEL:	upper explosive limit
URF:	unit risk factor
UST:	underground storage tank
UV:	ultraviolet

V

V:	volume
VAV:	variable air volume
VC:	vinyl chloride
Vertical VIPP:	vertical vapor intrusion preferential pathway
VFC:	vapor-forming chemical
VI:	vapor intrusion
VIM:	vapor intrusion model
VIMS:	vapor intrusion mitigation system
VIPP:	vapor intrusion preferential pathway
VISL:	vapor intrusion screening level
VOC:	volatile organic compound
VPH:	volatile petroleum hydrocarbon
VSS:	void space system

REFERENCES

Abbasi, Rafat, William Bosan, and Dan Gallagher. 2023. "Empirically Derived California Vapor Intrusion Attenuation Factors." *Groundwater Monitoring & Remediation* 43 (1): 60–68. https://doi.org/10.1111/gwmr.12559.

Abreu, L. D. V., R. Ettinger, and T. McAlary. 2009a. "Simulated Soil Vapor Intrusion Attenuation Factors Including Biodegradation for Petroleum Hydrocarbons." *Groundwater Monitoring & Remediation* 29 (1): 105–17. https://doi.org/10.1111/j.1745-6592.2008.01219.x.

Abreu, L. D. V., R. Ettinger, and T. McAlary. 2009b. "Simulating the Effect of Aerobic Biodegradation on Soil Vapor Intrusion into Buildings—Evaluation of Low Strength Sources Associated with Dissolved Gasoline Plumes." American Petroleum Institute.

Abreu, L. D. V., and P. C. Johnson. 2005. "Effect of Vapor Source–Building Separation and Building Construction on Soil Vapor Intrusion as Studied with a Three-Dimensional Numerical Model." *Environmental Science & Technology* 39 (12): 4550–61. https://doi.org/10.1021/es049781k.

Abreu, L. D. V., and P. C. Johnson. 2006. "Simulating the Effect of Aerobic Biodegradation on Soil Vapor Intrusion into Buildings: Influence of Degradation Rate, Source Concentration, and Depth." *Environmental Science & Technology* 40 (7): 2304–15. https://doi.org/10.1021/es051335p.

Alexander, M. 1999. *Biodegradation and Bioremediation*. 2nd ed. Academic Press.

Anders, K. 2012. "An Evaluation of Soil Vapor Intrusion (SVI) Manufactured Gas Plant (MGP) Sites." Association of State and Territorial Solid Waste Management Officials Annual Conference, Providence, Rhode Island, June.

API. 1994. *Transport and Fate of Non-BTEX Petroleum Chemicals in Soils and Groundwater*. American Petroleum Institute.

API. 2002. *Refinery Stream Specification*. No. 4723. American Petroleum Institute.

API. 2005. "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." American Petroleum Institute. https://www.api.org/~/media/files/ehs/clean_water/ground_water_quality/pub4741_vi_assessment_2005.pdf.

API. 2006. *Downward Solute Plume Migration: Assessment, Significance, and Implications for Characterization & Monitoring of "Diving Plumes."* API Soil & Groundwater Technical Task Force.

API. 2010. "BioVapor Indoor Vapor Intrusion Model." https://www.api.org/oil-and-natural-gas/environment/clean-water/ground-water/vapor-intrusion/biovapor.

API. 2012a. "BioVapor: A 1-D Vapor Intrusion Model with Oxygen-Limited Aerobic Biodegradation. Version 2.1." American Petroleum Institute, November. https://www.api.org/downloads/biovapor-users-guide.pdf.

API. 2012b. "User's Manual – BioVapor: A 1-D Vapor Intrusion Model with Oxygen-Limited Aerobic Biodegradation." American Petroleum Institute, November. https://www.api.org/downloads/biovapor-users-guide.pdf.

ASTM International. 2006a. *Standard Guide for Development of Conceptual Site Models and Remediation Strategies for Light Nonaqueous-Phase Liquids Released to the Subsurface*. Nos. E2531-06e1. ASTM International. https://www.astm.org/e2531-06r20.html.

ASTM International. 2006b. *Standard Guide for Soil Gas Monitoring in the Vadose Zone*. ASTM D5314-92. ASTM International.

ASTM International. 2009. *Standard Guide for Generation of Environmental Data Related to Waste Management Activities: Selection and Optimization of Sampling Design*. ASTM D6311-98. ASTM International.

ASTM International. 2015. *Standard Guide for Vapor Encroachment Screening on Property Involved in Real Estate Transactions*. ASTM E2600-10. ASTM International. https://store.astm.org/e2600-10.html.

ASTM International. 2021. *Standard Practice for Environmental Site Assessments: Phase I Environmental Site Assessment Process*. ASTM E1527-21. ASTM International. https://store.astm.org/e1527-21.html.

ASTM International. 2023. *Standard Guide for Evaluating Potential Hazard as a Result of Methane in the Vadose Zone*. ASTM E2993-16. ASTM International. https://store.astm.org/e2993-16.html.

ASTM International. 2024. *Standard Practice for Sonic Drilling for Site Characterization and the Installation of Subsurface Monitoring Devices*. ASTM D6914/D6914M-16. ASTM International. https://store.astm.org/d6914_d6914m-16.html.

Atkinson, B. 1968. "The Analogy Between Microbiological Reactions and Heterogeneous Catalysis." *Transactions of the Institution of Chemical Engineers* 46.

ATSDR. 2024a. "Minimal Risk Levels (MRLs)." Agency for Toxic Substances and Disease Registry, December. https://www.atsdr.cdc.gov/mrls/pdfs/ATSDR-MRLs-December-2024-H.pdf.

ATSDR. 2024b. "Toxicological Profile for Creosote." Agency for Toxic Substances and Disease Registry, July. https://www.atsdr.cdc.gov/toxprofiles/tp85.pdf.

Babich, H., and G. Stotzky. 1985. "Heavy Metal Toxicity to Microbe-Mediated Ecologic Processes: A Review and Potential Application to Regulatory Policies." *Environmental Research* 36 (1): 111–37. https://doi.org/10.1016/0013-9351(85)90011-8.

Beckley, Lila, Kyle Gorder, Erik Dettenmaier, Ignacio Rivera-Duarte, and Thomas McHugh. 2014. "On-Site Gas Chromatography/Mass Spectrometry (GC/MS) Analysis to Streamline Vapor Intrusion Investigations." *Environmental Forensics* 15 (3): 234–43. https://doi.org/10.1080/15275922.2014.930941.

Beckley, Lila, and Thomas McHugh. 2020. "A Conceptual Model for Vapor Intrusion from Groundwater through Sewer Lines." *Science of The Total Environment* 698 (January): 134283. https://doi.org/10.1016/j.scitotenv.2019.134283.

Bekele, Dawit N., Ravi Naidu, Mark Bowman, and Sreenivasulu Chadalavada. 2013. "Vapor Intrusion Models for Petroleum and Chlorinated Volatile Organic Compounds: Opportunities for Future Improvements." *Vadose Zone Journal* 12 (2): vzj2012.0048. https://doi.org/10.2136/vzj2012.0048.

Bekele, Dawit N., Ravi Naidu, and Sreenivasulu Chadalavada. 2014. "Influence of Spatial and Temporal Variability of Subsurface Soil Moisture and Temperature on Vapour Intrusion." *Atmospheric Environment* 88 (May): 14–22. https://doi.org/10.1016/j.atmosenv.2014.01.053.

Beringer, Mike. 2017. *Revised Vapor Intrusion Risk Management Decision Matrix*. https://semspub.epa.gov/work/07/30352706.pdf.

Bingham, Q. G., C. Lutes, R. Grand, et al. 2023. "Emissions of Trichloroethylene from Bedroom Furniture Set as a Source of Indoor Air Contamination." *Groundwater Monitoring & Remediation* 43 (1): 78–83. https://doi.org/10.1111/gwmr.12556.

Bosma, Tom N. P., Peter J. M. Middeldorp, Gosse Schraa, and Alexander J. B. Zehnder. 1997. "Mass Transfer Limitation of Biotransformation: Quantifying Bioavailability." *Environmental Science & Technology* 31 (1): 248–52. https://doi.org/10.1021/es960383u.

Boyer, J. 2004. "Background Contamination and Its Impact on the Assessment of Vapor Intrusion." Paper presented at Air and Waste Management Association Annual Conference and Exhibition, Indianapolis, IN.

Brewer, Roger, Josh Nagashima, Michael Kelley, Marvin Heskett, and Mark Rigby. 2013. "Risk-Based Evaluation of Total Petroleum Hydrocarbons in Vapor Intrusion Studies." *International Journal of Environmental Research and Public Health* 10 (6): 6. https://doi.org/10.3390/ijerph10062441.

Brewer, Roger, Josh Nagashima, Mark Rigby, Martin Schmidt, and Harry O'Neill. 2014. "Estimation of Generic Subslab Attenuation Factors for Vapor Intrusion Investigations." *Groundwater Monitoring & Remediation* 34 (4): 79–92. https://doi.org/10.1111/gwmr.12086.

California DTSC. 2004. "Guidance Document for the Implementation of United States Environmental Protection Agency Method 5035: Methodologies for Collection, Preservation, Storage, and Preparation of Soils to Be Analyzed for Volatile Organic Compounds."

California DTSC. 2011. "Final Guidance for the Evaluation and Mitigation of Subsurface Vapor Intrusion to Indoor Air (Vapor Intrusion Guidance)."

California DTSC. 2014. "Human Health Risk Assessment (HHRA) Note Number 5: Health-Based Indoor Air Screening Criteria for Trichloroethylene (TCE)." https://dtsc.ca.gov/wp-content/uploads/sites/31/2021/07/HHRA-Note-5-23-Aug-2014-2021-A.pdf.

California DTSC. 2015. "Advisory: Active Soil Gas Investigations." July. https://dtsc.ca.gov/wp-content/uploads/sites/31/2021/11/VI_ActiveSoilGasAdvisory_FINAL_a.pdf.

California DTSC. 2019. *Recommended DTSC Default Exposure Factors for Use in Risk Assessment at California Hazardous Waste Sites and Permitted Facilities*. Human Health Risk Assessment (HHRA) Note 1. Human and Ecological Risk Office (HERO).

California DTSC. 2021. *DTSC's Vapor Intrusion Database: Evaluation of Attenuation Factors for Buildings in California*. California Environmental Protection Agency, Department of Toxic Substances Control.

California DTSC. 2023. *Supplemental Guidance: Screening and Evaluating Vapor Intrusion*. https://dtsc.ca.gov/wp-content/uploads/sites/31/2023/02/VI_SupGuid_Screening-Evaluating.pdf.

California DTSC. 2024. *User's Guide — DTSC Implementation of the Johnson and Ettinger Model to Evaluate Vapor Intrusion into Buildings*. California Environmental Protection Agency, Department of Toxic Substances Control. https://dtsc.ca.gov/wp-content/uploads/sites/31/2024/11/DTSC-JEM-User-Guide_2024-October.pdf.

California Water Boards. 2012. "Technical Justification for Vapor Intrusion Media-Specific Criteria." https://www.waterboards.ca.gov/ust/docs/vi_tecjust.pdf.

California Water Boards. 2022. "Fact Sheet: Development on Properties with a Vapor Intrusion Threat — Updated June 2022." https://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/sitecleanup/2020_Fact_Sheet_Final.pdf.

California Water Boards. 2023. "Proposed Case Closure Former Jasco Chemical Company." San Francisco Bay Regional Water Quality Control Board, December. https://documents.geotracker.waterboards.ca.gov/regulators/deliverable_documents/8086011588/Frmr%20Jasco%20Mt%20View%20Closure%20fact%20sheet%20-%20final%202024-01-17.pdf.

California Water Boards. 2025. "Low-Threat Underground Storage Tank Case Closure Policy." California Water Boards (State Water Resources Control Board). https://www.waterboards.ca.gov/water_issues/programs/ust/lt_cls_plcy.html.

Carr, Daniel B., Laurent C. Levy, and Allan H. Horneman. 2010. "Vadose Zone Profiling to Better Understand Vadose Zone Processes Related to Vapor Intrusion." Air and Waste Management Association's Specialty Conference on Vapor Intrusion, Chicago, IL. https://www.clu-in.org/download/contaminantfocus/vi/vadose%20zone%20profiling%20to%20better.pdf.

CCME. 2010. "Review of Approaches for Modelling Vapour Migration into Trenches and Excavations." Canadian Council of Ministers of the Environment. https://ccme.ca/en/res/2011-n-hexane-review-of-approaches-for-modelling-vapour-migration-into-trenches-and-excavations-1455-en.pdf.

Chen, Yu Dao, James F. Barker, and Lai Gui. 2008. "A Strategy for Aromatic Hydrocarbon Bioremediation under Anaerobic Conditions and the Impacts of Ethanol: A Microcosm Study." *Journal of Contaminant Hydrology* 96 (1): 17–31. https://doi.org/10.1016/j.jconhyd.2007.09.006.

City of Milwaukee. 2024. "Milwaukee Code of Ordinances, Volume 2. Building and Zoning Code." City of Milwaukee. https://city.milwaukee.gov/ImageLibrary/Groups/ccClerk/Ordinances/Volume-2/Master-V2.pdf.

Control of Hazardous Air Pollutants From Mobile Sources, 72 Federal Register 8428 (2007). https://www.federalregister.gov/documents/2007/02/26/E7-2667/control-of-hazardous-air-pollutants-from-mobile-sources.

Creosote Council. 2025. "Timeline: A History of Creosote Wood Preservation." https://creosotecouncil.org/timeline/.

CSAP. 2024. "Review of Attenuation Factors and Partitioning." Contaminated Sites Approved Professionals of British Columbia. https://csapsociety.bc.ca/wp-content/uploads/MEMS-Review-of-Attenuation-Factors-and-Partitioning-Report-May-2024.pdf.

Davis, G. B., B. M. Patterson, and C. D. Johnston. 2009. "Aerobic Bioremediation of 1,2 Dichloroethane and Vinyl Chloride at Field Scale." *Journal of Contaminant Hydrology* 107 (1): 91–100. https://doi.org/10.1016/j.jconhyd.2009.04.004.

Davis, G. B., B. M. Patterson, and M. G. Trefry. 2009. "Evidence for Instantaneous Oxygen-Limited Biodegradation of Petroleum Hydrocarbon Vapors in the Subsurface." *Groundwater Monitoring & Remediation* 29 (1): 126–37. https://doi.org/10.1111/j.1745-6592.2008.01221.x.

Davis, R. V. 2009. "Bioattenuation of Petroleum Hydrocarbon Vapors in the Subsurface: Update on Recent Studies and Proposed Screening Criteria for the Vapor-Intrusion Pathway." *L.U.S.T. Line Bulletin* 31: 11–14.

Dawson, Helen E., and Todd McAlary. 2009. "A Compilation of Statistics for VOCs from Post-1990 Indoor Air Concentration Studies in North American Residences Unaffected by Subsurface Vapor Intrusion." *Groundwater Monitoring & Remediation* 29 (1): 60–69. https://doi.org/10.1111/j.1745-6592.2008.01215.x.

DeHate, Robin B., Giffe T. Johnson, and Raymond D. Harbison. 2011. "Risk Characterization of Vapor Intrusion in Former Manufactured Gas Plant Sites." *Regulatory Toxicology and Pharmacology* 59 (2): 353–59. https://doi.org/10.1016/j.yrtph.2010.12.001.

DeVaull, G. E. 2007. "Indoor Vapor Intrusion with Oxygen-Limited Biodegradation for a Subsurface Gasoline Source." *Environmental Science & Technology* 41 (9): 3241–48.

DeVaull, G. E. 2011. "Biodegradation Rates for Petroleum Hydrocarbons in Aerobic Soils: A Summary of Measured Data." International Symposium on Bioremediation and Sustainable Environmental Technologies, Reno, Nevada.

DeVaull, G. E., R. A. Ettinger, J. P. Salanitro, and J. B. Gustafson. 1997. *Benzene, Toluene, Ethylbenzene, and Xylenes (BTEX) Degradation in Vadose Zone Soils during Vapor Transport: First-Order Rate Constants*. CONF-971116-. December 31, CONF-971116-. https://www.osti.gov/biblio/569942.

Devries, Jarod Michael. 2017. "Experimental Investigation on the Fate of Ethanol-Blended Fuels in the Subsurface." University of British Columbia. https://doi.org/10.14288/1.0348668.

Doucette, W. J., A. J. Hall, and K. A. Gorder. 2010. "Emissions of 1,2-Dichloroethane from Holiday Decorations as a Source of Indoor Air Contamination." *Groundwater Monitoring & Remediation* 30 (1): 67–73. https://doi.org/10.1111/j.1745-6592.2009.01267.x.

Einarson, Murray, Adrian Fure, Randy St. Germain, Steven Chapman, and Beth Parker. 2018. "DyeLIF™: A New Direct-Push Laser-Induced Fluorescence Sensor System for Chlorinated Solvent DNAPL and Other Non-Naturally Fluorescing NAPLs." *Groundwater Monitoring & Remediation* 38 (3): 28–42. https://doi.org/10.1111/gwmr.12296.

Eklund, Bart. 2024. "Climatic Effects on Vapor Flow and Behavior in the Vadose Zone." *Groundwater Monitoring & Remediation* 44 (4): 80–91. https://doi.org/10.1111/gwmr.12682.

Eklund, Bart, Catherine Regan, Rich Rago, and Lila Beckley. 2024. "Overview of State Approaches to Vapor Intrusion: 2023 Update." *Groundwater Monitoring & Remediation* 44 (3): 76–93. https://doi.org/10.1111/gwmr.12627.

Eklund, Bart, Carly Ricondo, Helen Artz-Patton, Jessica Milose, and Chi-Wah Wong. 2023. "Development of a Default Vapor Intrusion Attenuation Factor for Industrial Buildings." *Groundwater Monitoring & Remediation* 43 (1): 35–43. https://doi.org/10.1111/gwmr.12534.

EPRI. 1993. *Chemical and Physical Characteristics of Tar Samples From Selected Manufactured Gas Plant (MGP) Sites*. TR-102184. Electric Power Research Institute. https://health.hawaii.gov/heer/files/2021/07/EPRI1993.pdf.

EPRI. 1999. *Survey of Chemical and Physical Properties of Soils Collected from Former Manufactured Gas Plant Sites*. EPRI-TR-114192. Electric Power Research Institute.

EPRI. 2007. *Residential Indoor Air Background Data: A Comparison of Indoor Air Results from Vapor Intrusion Studies at MGP Sites in New York*. Report 1012590. Electric Power Research Institute.

ESTCP. 2011. *A Guide for Selecting Remedies for Subsurface Releases of Chlorinated Solvents*. ER-200530. Department of Defense Environmental Security Technology Certification Program. https://sepub-prod-0001-124733793621-us-gov-west-1.s3.us-gov-west-1.amazonaws.com/s3fs-public/project_documents/ER-200530-DG.pdf?VersionId=ENhLkogP.8bk3nQHDffbvE4gbbyrR1ZW.

ESTCP. 2025. *Mass Flux Characterization for Vapor Intrusion Assessment – Final Report*. ESTCP Project ER-201503. Department of Defense Environmental Security Technology Certification Program. https://serdp-estcp.mil/projects/details/a6dd2239-5eb3-46ee-ac57-180aaff7e9d2.

Fan, A., and E.A. Quinn. 2000. "Case Study: Residential Indoor Air Assessment above a Hydrocarbon Plume." Presentation to US EPA EI Forum. RCRA National Conference, Washington, D.C, August.

Fischer, Marc L., Abra J. Bentley, Kristie A. Dunkin, et al. 1996. "Factors Affecting Indoor Air Concentrations of Volatile Organic Compounds at a Site of Subsurface Gasoline Contamination." *Environmental Science & Technology* 30 (10): 2948–57. https://doi.org/10.1021/es950912e.

Fitzpatrick, Nancy A., and John J. Fitzgerald. 2002. "An Evaluation of Vapor Intrusion Into Buildings through a Study of Field Data." *Soil and Sediment Contamination: An International Journal* 11 (4): 603–23. https://doi.org/10.1080/20025891107186.

Folkes, D. J., and J. Arell. 2001. "Vapor Intrusion: Evaluating the Unseen Pathway." *Environmental Forensics* 2 (4).

Folkes, D. J., J. P. Kurtz, and C. Sanpawanitchakit. 2007. "Lateral Extent of Vapor Intrusion Impacts." AWMA Vapor Intrusion Conference, Providence, RI.

Folkes, D. J., and C. Sanpawanitchakit. 2011. *Modeling of Vapor Intrusion Mitigation*. https://www.researchgate.net/publication/320067948_Modeling_of_vapor_intrusion_mitigation.

Folkes, D. J., W. Wertz, J. Kurtz, and T. Kuehster. 2009. "Observed Spatial and Temporal Distributions of CVOCs at Colorado and New York Vapor Intrusion Sites." *Groundwater Monitoring & Remediation* 29 (1): 70–80. https://doi.org/10.1111/j.1745-6592.2009.01216.x.

Freeman, M. H., T. F. Shupe, R. Vlosky, and H. M. Barnes. 2003. "Past, Present, and Future of the Wood Preservation Industry." *Forest Products Journal* 53 (10): 8–15.

Gibbs, L. M. 1982. *Love Canal: My Story*. State University of New York Press.

Golder Associates Ltd. 2007. *Evaluation of Vadose Zone Biodegradation of Petroleum Hydrocarbons: Implications for Vapour Intrusion Guidance*. Health Canada and Canadian Petroleum Products Institute.

Haghighat, F., C.-S. Lee, and W. S Ghaly. 2002. "Measurement of Diffusion Coefficients of VOCs for Building Materials: Review and Development of a Calculation Procedure: Abstract." *Indoor Air* 12 (2): 81–91. https://doi.org/10.1034/j.1600-0668.2002.1e008.x.

Hallberg, Keri E., Laurent C. Levy, Rodrigo Gonzalez-Abraham, Christopher C. Lutes, Loren G. Lund, and Donna Caldwell. 2021. "An Alternative Generic Subslab Soil Gas-to-Indoor Air Attenuation Factor for Application in Commercial, Industrial, and Other Nonresidential Settings." *Journal of the Air & Waste Management Association* 71 (9): 1148–58. https://doi.org/10.1080/10962247.2021.1930286.

Hartman, B. 1998. "The Great Escape (from the UST)." *LUSTLine Bulletin 30*. https://hartmaneg.com/wp-content/uploads/2021/02/Great-Escape-from-the-UST.pdf.

Hartman, B. 2006. "How to Collect Reliable Soil Gas Data for Risk-Based Applications, Specifically Vapor Intrusion: Part 4—Updates on Soil Gas Collection and Analytical Procedures." *L.U.S.T.Line Bulletin 53*.

Hawaii Department of Health. 2012. "Field Investigation of the Chemistry and Toxicity of TPH in Petroleum Vapors: Implications for Potential Vapor Intrusion Hazards." http://www.hawaiidoh.org/tgm-guidance/TPH%20Soil%20Gas%20Report%20(HDOH%20August%202012).pdf.

Hayes, H. 2007. *Evaluation of Sorbent Methodology for Petroleum-Impacted Site Investigations*. Vapor Intrusion: Learning from the Challenges. Air & Waste Management Association. https://www.eurofinsus.com/media/15876/evaluation-of-sorbent-methodology-for-petroleum-impacted-site-investigations.pdf.

Hayes, H., C. Lutes, N. Watson, et al. 2024. "Laboratory Development and Validation of Vapor Phase PFAS Methods for Soil Gas, Sewer Gas, and Indoor Air." *Environmental Science: Atmospheres* 5 (1): 94–109. https://doi.org/10.1039/d4ea00084f.

Health Canada. 2023. "Federal Contaminated Site Risk Assessment in Canada: Supplemental Guidance for Soil Vapour Intrusion Assessment at Federal Contaminated Sites." February. https://publications.gc.ca/collections/collection_2023/sc-hc/H129-135-2022-eng.pdf.

Hers, Ian, Jim Atwater, Loretta Li, and Reidar Zapf-Gilje. 2000. "Evaluation of Vadose Zone Biodegradation of BTX Vapours." *Journal of Contaminant Hydrology* 46 (3): 233–64. https://doi.org/10.1016/S0169-7722(00)00135-2.

Hers, Ian, Parisa Jourabchi, Matthew A. Lahvis, et al. 2014. "Evaluation of Seasonal Factors on Petroleum Hydrocarbon Vapor Biodegradation and Intrusion Potential in a Cold Climate." *Groundwater Monitoring & Remediation* 34 (4): 60–78. https://doi.org/10.1111/gwmr.12085.

Hers, Ian, John T. Wilson, Ravi V. Kolhatkar, Matthew A. Lahvis, Emma (Hong) Luo, and Parisa Jourabchi. 2022. "Field Study of Vertical Screening Distance Criteria for Vapor Intrusion of Ethylene Dibromide." *Groundwater Monitoring & Remediation* 42 (1): 65–80. https://doi.org/10.1111/gwmr.12484.

Hers, Ian, and Reidar Zapf-Gilje. 1998. "Canadian Consortium Research Project: Field Validation of Soil Gas Transport to Indoor Air Pathway." *Proceedings of the 1998 Petroleum Hydrocarbon and Organic Chemicals in Groundwater Conference.* (Houston, TX), 251–66.

Hers, Ian, Reidar Zapf-Gilje, Dyfed Evans, and Loretta Li. 2002. "Comparison, Validation, and Use of Models for Predicting Indoor Air Quality from Soil and Groundwater Contamination." *Soil and Sediment Contamination: An International Journal* 11 (4): 491–527. https://doi.org/10.1080/20025891107140.

Hers, Ian, Reidar Zapf-Gilje, Paul C. Johnson, and Loretta Li. 2003. "Evaluation of the Johnson and Ettinger Model for Prediction of Indoor Air Quality." *Groundwater Monitoring & Remediation* 23 (2): 119–33. https://doi.org/10.1111/j.1745-6592.2003.tb00678.x.

Hesse, Falk, Hauke Harms, Sabine Attinger, and Martin Thullner. 2010. "Linear Exchange Model for the Description of Mass Transfer Limited Bioavailability at the Pore Scale." *Environmental Science & Technology* 44 (6): 2064–71. https://doi.org/10.1021/es902489q.

Holden, Patricia A., Larry J. Halverson, and Mary K. Firestone. 1997. "Water Stress Effects on Toluene Biodegradation by Pseudomonas Putida." *Biodegradation* 8 (3): 143–51. https://doi.org/10.1023/A:1008237819089.

Holton, Chase, Hong Luo, Paul Dahlen, Kyle Gorder, Erik Dettenmaier, and Paul C. Johnson. 2013. "Temporal Variability of Indoor Air Concentrations under Natural Conditions in a House Overlying a Dilute Chlorinated Solvent Groundwater Plume." *Environmental Science & Technology* 47 (23): 13347–54. https://doi.org/10.1021/es4024767.

Hopkin, P. 2007. *Oil and Gas Pipelines: Yesterday and Today*. Penspen, Ltd.

Hosangadi, Vitthal, Brandon Shaver, Blayne Hartman, Michael Pound, Mark L. Kram, and Cliff Frescura. 2017. "High-Frequency Continuous Monitoring to Track Vapor Intrusion Resulting From Naturally Occurring Pressure Dynamics." *Remediation Journal* 27 (2): 9–25. https://doi.org/10.1002/rem.21505.

Hubbard, Lynn Marie, and Nils Hagberg. 1996. "Time-Variation of the Soil Gas Radon Concentration under and near a Swedish House." *Environment International*, The Natural Radiation Environment VI, vol. 22 (January): 477–82. https://doi.org/10.1016/S0160-4120(96)00148-1.

IDEM. 2022. *Risk-Based Closure Guide*. Indiana Department of Environmental Management Office of Land Quality. https://www.in.gov/idem/files/nrpd_waste-0046-r2_attch.pdf.

ITRC. 2003. *Technical and Regulatory Guidance for the Triad Approach: A New Paradigm for Environmental Project Management*. Interstate Technology & Regulatory Council. https://itrcweb.org/wp-content/uploads/2024/09/SCM-1.pdf.

ITRC. 2004. *Technical and Regulatory Guidance for Using Polyethylene Diffusion Bag Samplers to Monitor Volatile Organic Compounds in Gr...* Interstate Technology & Regulatory Council. https://itrcweb.org/wp-content/uploads/2024/09/DSP-3.pdf.

ITRC. 2007. *Vapor Intrusion Pathway: A Practical Guideline*. Interstate Technology & Regulatory Council.

ITRC. 2011. *Biofuels: Release Prevention, Environmental Behavior, and Remediation*. Interstate Technology & Regulatory Council. https://itrcweb.org/wp-content/uploads/2024/09/biofuels-1.pdf.

ITRC. 2014. *Petroleum Vapor Intrusion: Fundamentals of Screening, Investigation, and Management*. Interstate Technology & Regulatory Council.

ITRC. 2015. "Decision Making at Contaminated Sites." January. https://projects.itrcweb.org/risk-3/.

ITRC. 2016. *Long-Term Contaminant Management Using Institutional Controls*. Interstate Technology & Regulatory Council.

ITRC. 2018. "LNAPL Site Management: LCSM Evolution, Decision Process, and Remedial Technologies." In *LNAPL-3*. Interstate Technology & Regulatory Council, LNAPLs Team. https://lnapl-3.itrcweb.org.

ITRC. 2019. "Implementing Advanced Site Characterization Tools." https://asct-1.itrcweb.org/.

ITRC. 2020a. *Appendix H. Communication Methods Summary Table – Risk Communication Toolkit*. Interstate Technology & Regulatory Council. https://rct-1.itrcweb.org/appendix-h-communication-methods-summary-table/.

ITRC. 2020b. *Risk Communication Toolkit*. Interstate Technology & Regulatory Council. https://rct-1.itrcweb.org/.

ITRC. 2023. *PFAS — Per- and Polyfluoroalkyl Substances*. Interstate Technology & Regulatory Council. https://pfas-1.itrcweb.org/.

ITRC. 2024. *Passive Sampling Technology Update*. Interstate Technology & Regulatory Council. https://psu-1.itrcweb.org/.

Jeng, C. Y., V. J. Kremesec, and H. S. Primack. 1996. "Models of Hydrocarbon Vapor Diffusion through Soil and Transport into Buildings." Paper presented at Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection and Remediation Conference, Houston, TX.

Jewell, Kenneth P., and John T. Wilson. 2011. "A New Screening Method for Methane in Soil Gas Using Existing Groundwater Monitoring Wells." *Groundwater Monitoring & Remediation* 31 (3): 82–94. https://doi.org/10.1111/j.1745-6592.2011.01345.x.

Johnson, P. C. 2005. "Identification of Application-Specific Critical Inputs for the 1991 Johnson and Ettinger Vapor Intrusion Algorithm." *Groundwater Monitoring & Remediation* 25 (1): 63–78. https://doi.org/10.1111/j.1745-6592.2005.0002.x.

Johnson, P. C., and R. A. Ettinger. 1991. "Heuristic Model for Predicting the Intrusion Rate of Contaminant Vapors into Buildings." *Environmental Science & Technology* 25 (8): 1445–52. https://doi.org/10.1021/es00020a013.

Johnson, P. C., V. A. Hermes, and S. Roggemans. 2000. "An Oxygen-Limited Hydrocarbon Vapor Migration Attenuation Screening Model." Written communication. Arizona State University.

Johnson, P. C., C. Holton, Y. Guo, P. Dahlen, and H. Luo. 2016. *Integrated Field-Scale, Lab-Scale, and Modeling Studies for Improving Our Ability to Assess the Groundwater to Indoor Air Pathway at Chlorinated Solvent-Impacted Groundwater Sites*. SERDP Project ER-1686. Arizona State University. https://sepub-prod-0001-124733793621-us-gov-west-1.s3.us-gov-west-1.amazonaws.com/s3fs-public/2024-07/Final%20Report%20V2%20ER-1686%20July%202016.pdf?VersionId=uPH8U3jdu4UM5Gsb8u40RjfVyKb_3WTm.

Johnson, P. C., M. W. Kemblowski, and J. D. Colthart. 1990. "Quantitative Analysis for the Cleanup of Hydrocarbon-Contaminated Soils by In-Situ Soil Venting." *Groundwater* 28 (3): 413–29. https://doi.org/10.1111/j.1745-6584.1990.tb02271.x.

Johnson, P. C., M. W. Kemblowski, and R. L. Johnson. 1998. *Assessing the Significance of Subsurface Contaminant Vapor Migration to Enclosed Spaces: Site-Specific Alternatives to Generic Estimates*. American Petroleum Institute. https://www.api.org/oil-and-natural-gas/environment/clean-water/ground-water/vapor-intrusion/vi-publication/%7E/media/72FCCA0B02D0440AA7510C7CFE296CF3.ashx.

Johnson, P. C., M. W. Kemblowski, and R. L. Johnson. 1999. "Assessing the Significance of Subsurface Contaminant Vapor Migration to Enclosed Spaces: Site-Specific Alternatives to Generic Estimates." *Soil and Sediment Contamination* 8 (3): 389–421.

Jourabchi, P., N. Sihota, I. Hers, G. DeVaull, R. Kolhatkar, and B. Bauman. 2012. "Effects of Ethanol Blended Gasoline Release on Soil Vapor Transport: Preliminary Results of Biogas Generation Experiments and Numerical Modeling." *ResearchGate*, 155–84. https://www.researchgate.net/publication/286319584_Effects_of_ethanol_blended_gasoline_release_on_soil_vapor_transport_Preliminary_results_of_biogas_generation_experiments_and_numerical_modeling.

Jury, W. A., D. Russo, G. Streile, and H. El Abd. 1990. "Evaluation of Volatilization by Organic Chemicals Residing below the Soil Surface." *Water Resources Research* 26 (1): 13–20. https://doi.org/10.1029/WR026i001p00013.

Jury, W. A., W. F. Spencer, and W. J. Farmer. 1983. "Behavior Assessment Model for Trace Organics in Soil: I. Model Description." *Journal of Environmental Quality* 12 (4): 558–64. https://doi.org/10.2134/jeq1983.00472425001200040025x.

Kissel, John C., Perry L. McCarty, and Robert L. Street. 1984. "Numerical Simulation of Mixed-Culture Biofilm." *Journal of Environmental Engineering* 110 (2): 393–411. https://doi.org/10.1061/(ASCE)0733-9372(1984)110:2(393).

Kissel, John C., Perry L. McCarty, and Robert L. Street. 1985. "Closure to '*Numerical Simulation of Mixed-Culture Biofilm*' by John C. Kissel, Perry L. McCarty, and Robert L. Street (April 1984)." *Journal of Environmental Engineering* 111 (4): 549–51. https://doi.org/10.1061/(ASCE)0733-9372(1985)111:4(549).

Kobayashi, Kazusuke, and Keizoh Shuttoh. 1991. "Oxygen Diffusivity of Various Cementitious Materials." *Cement and Concrete Research* 21 (2): 273–84. https://doi.org/10.1016/0008-8846(91)90009-7.

Kolhatkar, Ravi V., Matthew A. Lahvis, Ian Hers, John T. Wilson, Emma (Hong) Luo, and Parisa Jourabchi. 2019. "Vertical Screening Distance Criteria to Evaluate Vapor Intrusion Risk from 1,2-Dichloroethane (1,2-DCA)." *Groundwater Monitoring & Remediation* 39 (4): 41–51. https://doi.org/10.1111/gwmr.12351.

Kolhatkar, Ravi V., Emma (Hong) Luo, Erin C. Berns, Christopher Gaule, and Joe Watterson. 2021. "Evaluation of Vapor Intrusion Risk from Ethylene Dibromide Using the Vertical Screening Distance Approach." *Groundwater Monitoring & Remediation* 41 (2): 48–60. https://doi.org/10.1111/gwmr.12442.

Kram, M. L. 1998. "Use of SCAPS Petroleum Hydrocarbon Sensor Technology for Real-Time Indirect DNAPL Detection." *Journal of Soil Contamination* 7 (1): 73–86. https://doi.org/10.5555/19981905611.

Kram, M. L. 2002. "DNAPL Contaminant Detection Using Optimized Fluorescence Methods." Ph.D. Dissertation, University of California, Santa Barbara.

Kram, M. L. 2006. "DNAPL Characterization Methods and Approaches: Performance and Cost Comparisons." In *The Practical Handbook of Environmental Site Characterization and Ground-Water Monitoring*. CRC Press/Taylor & Francis Publishers.

Kram, M. L., B. Hartman, and N. Clite. 2019. "Automated Continuous Monitoring and Response to Toxic Subsurface Vapors Entering Overlying Buildings—Selected Observations, Implications and Considerations." *Remediation Journal* 29 (3): 31–38. https://doi.org/10.1002/rem.21605.

Kram, M. L., B. Hartman, and C. Frescura. 2016. "Vapor Intrusion Monitoring Method Cost Comparisons: Automated Continuous Analytical Versus Discrete Time-Integrated Passive Approaches." *Remediation Journal* 26 (4): 41–52. https://doi.org/10.1002/rem.21482.

Kram, M. L., B. Hartman, and C. Frescura. 2022. "Simultaneous Monitoring of Volatile Organic Contaminant Concentration and Controlling Factors for Vapor Intrusion Risk Evaluations—Two Select Cases." *Remediation Journal* 32 (4): 259–72. https://doi.org/10.1002/rem.21728.

Kram, M. L., B. Hartman, C. Frescura, P. Negrao, and D. Egelton. 2020. "Vapor Intrusion Risk Evaluation Using Automated Continuous Chemical and Physical Parameter Monitoring." *Remediation Journal* 30 (3): 65–74. https://doi.org/10.1002/rem.21646.

Kram, M. L., and R. Solgi. 2025. "Empirically-Derived Building-Specific Learning Models for Predicting Occupant Vapor Intrusion Exposures." *Remediation Journal* 35 (2): e70016. https://doi.org/10.1002/rem.70016.

Kuehster, T. E., D. J. Folkes, and E. J. Wannamaker. 2004. "Seasonal Variation of Observed Indoor Air Concentrations Due to Vapor Intrusion." Midwestern States Risk Assessment Symposium, Indianapolis, IN.

Lahvis, Matthew A. 2011. "Vapour Transport from Soil and Groundwater to Indoor Air: Analytical Modelling Approach." In *Vapor Emission to Outdoor Air and Enclosed Spaces*. Nova Science Publishers, Inc. https://www.researchgate.net/publication/320067943_Vapour_transport_from_soil_and_groundwater_to_indoor_air_Analytical_modelling_approach.

Lahvis, Matthew A. 2018. "Vertical Screening Distances for Total Petroleum Hydrocarbon for Vapour Intrusion Risk Assessment at Petroleum Underground Storage Tank Sites." *Quarterly Journal of Engineering Geology and Hydrogeology* 51 (February): 3–12. https://doi.org/10.1144/qjegh2017-009.

Lahvis, Matthew A., and Arthur L. Baehr. 1997. "Documentation of R-UNSAT, a Computer Model for the Simulation of Reactive, Multispecies Transport in the Unsaturated Zone." In *Open-File Report*, Nos. 97–630. U.S. Geological Survey. https://doi.org/10.3133/ofr97630.

Lahvis, Matthew A., Arthur L. Baehr, and Ronald J. Baker. 1999. "Quantification of Aerobic Biodegradation and Volatilization Rates of Gasoline Hydrocarbons near the Water Table under Natural

Attenuation Conditions." *Water Resources Research* 35 (3): 753–65. https://doi.org/10.1029/1998WR900087.

Lahvis, Matthew A., and Robert A. Ettinger. 2021. "Improving Risk-Based Screening at Vapor Intrusion Sites in California." *Groundwater Monitoring & Remediation* 41 (2): 73–86. https://doi.org/10.1111/gwmr.12450.

Lahvis, Matthew A., Ian Hers, Robin V. Davis, Jackie Wright, and George E. DeVaull. 2013. "Vapor Intrusion Screening at Petroleum UST Sites." *Groundwater Monitoring & Remediation* 33 (2): 53–67. https://doi.org/10.1111/gwmr.12005.

Laubacher, R. C., P. Bartholomae, P. Velasco, and H. J. Reisinger. 1997. "An Evaluation of the Vapor Profile in the Vadose Zone above a Gasoline Plume." *Proceedings of the 1997 Petroleum Hydrocarbon and Organic Chemicals in Groundwater Conference* (Houston, TX), 396–409.

Leeson, A, and R. E. Hinchee. 1996. *Principles and Practices of Bioventing. Volume 1: Bioventing Principles and Volume 2: Bioventing Design*. Battelle Memorial Institute.

Levy, Laurent C., Keri E. Hallberg, Rodrigo Gonzalez-Abraham, et al. 2023. "An Alternative Generic Groundwater-to-Indoor Air Attenuation Factor for Application in Commercial, Industrial, and Other Nonresidential Settings." *Journal of the Air & Waste Management Association* 73 (4): 258–70. https://doi.org/10.1080/10962247.2023.2175740.

Little, John C., Joan M. Daisey, and William W. Nazaroff. 1992. "Transport of Subsurface Contaminants into Buildings." *ACS Publications*, Environmental Science & Technology, vol. 26 (11): 2058–66. world. https://doi.org/10.1021/es00035a001.

Loureiro, Celso O., Linda M. Abriola, James E. Martin, and Richard G. Sextro. 1990. "Three-Dimensional Simulation of Radon Transport into Houses with Basements under Constant Negative Pressure." *Environmental Science & Technology* 24 (9): 1338–48. https://doi.org/10.1021/es00079a007.

Lowell, Philip S., and Bart Eklund. 2004. "VOC Emission Fluxes as a Function of Lateral Distance from the Source." *Environmental Progress* 23 (1): 52–58. https://doi.org/10.1002/ep.10007.

Lundegard, Paul D., Paul C. Johnson, and Paul Dahlen. 2008. "Oxygen Transport From the Atmosphere to Soil Gas Beneath a Slab-on-Grade Foundation Overlying Petroleum-Impacted Soil." *Environmental Science & Technology* 42 (15): 5534–40. https://doi.org/10.1021/es070607g.

Luo, H., P. Dahlen, P. Johnson, et al. 2006. "Spatial and Temporal Variability in Hydrocarbon and Oxygen Concentrations Beneath a Building Above a Shallow NAPL Source." Remediation of Chlorinated and Recalcitrant Compounds, Monterey, CA.

Luo, H., P. Dahlen, P. C. Johnson, T. Peargin, and T. Creamer. 2009. "Spatial Variability of Soil-Gas Concentrations near and beneath a Building Overlying Shallow Petroleum Hydrocarbon–Impacted Soils." *Groundwater Monitoring & Remediation* 29 (1): 81–91. https://doi.org/10.1111/j.1745-6592.2008.01217.x.

Luo, H., P. Dahlen, P. Johnson, and T. Peargin. 2013. "Proof-of-Concept Study of an Aerobic Vapor Migration Barrier beneath a Building at a Petroleum Hydrocarbon-Impacted Site." *Environmental Science & Technology* 47 (4): 1977–84.

Lutes, Christopher C., Chase W. Holton, Brian Schumacher, John H. Zimmerman, Andrew Kondash, and Robert Truesdale. 2021. "Observation of Conditions Preceding Peak Indoor Air Volatile Organic

Compound Concentrations in Vapor Intrusion Studies." *Groundwater Monitoring & Remediation* 41 (2): 99–111. https://doi.org/10.1111/gwmr.12452.

Lutes, Christopher C., Chase W. Holton, Robert Truesdale, John H. Zimmerman, and Brian Schumacher. 2019. "Key Design Elements of Building Pressure Cycling for Evaluating Vapor Intrusion—A Literature Review." *Groundwater Monitoring & Remediation* 39 (1): 66–72. https://doi.org/10.1111/gwmr.12310.

Ma, Jie, Haiyan Li, Richard Spiese, John Wilson, Guangxu Yan, and Shaohui Guo. 2016. "Vapor Intrusion Risk of Lead Scavengers 1,2-Dibromoethane (EDB) and 1,2-Dichloroethane (DCA)." *Environmental Pollution* 213 (June): 825–32. https://doi.org/10.1016/j.envpol.2016.03.032.

Ma, Jie, Hong Luo, George E. DeVaull, William G. Rixey, and Pedro J. J. Alvarez. 2014. "Numerical Model Investigation for Potential Methane Explosion and Benzene Vapor Intrusion Associated with High-Ethanol Blend Releases." *Environmental Science & Technology* 48 (1): 474–81. https://doi.org/10.1021/es403926k.

Ma, Jie, Thomas McHugh, Lila Beckley, Matthew Lahvis, George DeVaull, and Lin Jiang. 2020. "Vapor Intrusion Investigations and Decision-Making: A Critical Review." *Environmental Science & Technology* 54 (12): 7050–69. https://doi.org/10.1021/acs.est.0c00225.

Margesin, R., and F. Schinner. 2001. "Biodegradation and Bioremediation of Hydrocarbons in Extreme Environments." *Applied Microbiology and Biotechnology* 56 (5): 650–63. https://doi.org/10.1007/s002530100701.

MassDEP. 2016. *Vapor Intrusion Guidance: Site Assessment, Mitigation and Closure*. Massachusetts Department of Environmental Protection. https://www.mass.gov/doc/wsc-16-435-vapor-intrusion-guidance-site-assessment-mitigation-and-closure/download.

MassDEP and ABB Environmental Services, Inc. 1994. *Interim Final Petroleum Report: Development of Health-Based Alternative to the Total Petroleum Hydrocarbon (TPH) Parameter*. Massachusetts Department of Environmental Protection and ABB Environmental Services, Inc.

Mayer, K. Ulrich, Emil O. Frind, and David W. Blowes. 2002. "Multicomponent Reactive Transport Modeling in Variably Saturated Porous Media Using a Generalized Formulation for Kinetically Controlled Reactions." *Water Resources Research* 38 (9): 13-1-13–21. https://doi.org/10.1029/2001WR000862.

McAlary, T. A., and T. Cramer. 2006. "The Effects of Purge Rate and Volume on Sub-Slab Soil Gas Samples." Remediation of Chlorinated and Recalcitrant Compounds, Monterey, CA.

McAlary, T. A., P. Dollar, P. de Haven, et al. 2002. "Assessment of Subsurface Vapour Transport Through Triassic Sandstone and Quarry Fill into Indoor Air in Weston Village, Runcorn." Indoor Air 2002, Monterey, CA.

McAlary, T. A., J. Gallinatti, G. Thrupp, W. Wertz, D. Mali, and H. Dawson. 2018. "Fluid Flow Model for Predicting the Intrusion Rate of Subsurface Contaminant Vapors into Buildings." *Environmental Science & Technology* 52 (15): 8438–45. https://doi.org/10.1021/acs.est.8b01106.

McAlary, T. A., P. J. Nicholson, L. K. Yik, D. M. Bertrand, and G. Thrupp. 2010. "High Purge Volume Sampling—A New Paradigm for Subslab Soil Gas Monitoring." *Groundwater Monitoring & Remediation* 30 (2): 73–85. https://doi.org/10.1111/j.1745-6592.2010.01278.x.

McAlary, T. A., W. Wertz, and D. Mali. 2018. *Demonstration/Validation of More Cost-Effective Methods for Mitigating Radon and VOC Subsurface Vapor Intrusion to Indoor Air*. U.S. Department of Defense: ESTCP. https://clu-in.org/download/issues/vi/ER-201322-Final-Report.pdf.

McAlary, T. A., W. Wertz, D. Mali, and P. Nicholson. 2020. "Mathematical Analysis and Flux-Based Radius of Influence for Radon/VOC Vapor Intrusion Mitigation Systems." *Science of the Total Environment* 740 (139988).

McHugh, Thomas E., and Lila Beckley. 2018. "Sewers and Utility Tunnels as Preferential Pathways for Volatile Organic Compound Migration into Buildings: Risk Factors and Investigation Protocol." Department of Defense Environmental Security Technology Certification Program, November. https://www.erwiki.net/images/5/55/2018b-McHugh-ER-201505_Conceptual_Model.pdf.

McHugh, Thomas E., Lila Beckley, Danielle Bailey, et al. 2012. "Evaluation of Vapor Intrusion Using Controlled Building Pressure." *Environmental Science & Technology* 46 (9): 4792–99. https://doi.org/10.1021/es204483g.

McHugh, Thomas E., John A. Connor, and Ahmad Farrukh. 2004. "An Empirical Analysis of the Groundwater-to-Indoor-Air Exposure Pathway: The Role of Background Concentrations in Indoor Air." *Environmental Forensics* 5 (1): 33–44. https://doi.org/10.1080/15275920490424024.

McHugh, Thomas E., Robin Davis, George E. DeVaull, Harley Hopkins, John Menatti, and Tom Peargin. 2010. "Evaluation of Vapor Attenuation at Petroleum Hydrocarbon Sites: Considerations for Site Screening and Investigation." *Soil and Sediment Contamination: An International Journal* 19 (6): 725–45. https://doi.org/10.1080/15320383.2010.499923.

McHugh, Thomas E., Phillip C. De Blanc, and Roger J. Pokluda. 2006. "Indoor Air as a Source of VOC Contamination in Shallow Soils Below Buildings." *Soil and Sediment Contamination: An International Journal* 15 (1): 103–22. https://doi.org/10.1080/15320380500364473.

McHugh, Thomas E., Per Loll, and Bart Eklund. 2017. "Recent Advances in Vapor Intrusion Site Investigations." *Journal of Environmental Management*, Global Trends in the Environmental Remediation Industry, vol. 204 (December): 783–92. https://doi.org/10.1016/j.jenvman.2017.02.015.

McHugh, Thomas E., Carlyssa Villarreal, Lila M. Beckley, and Sharon R. Rauch. 2018. "Evidence of Canister Contamination Causing False Positive Detections in Vapor Intrusion Investigation Results." *Soil and Sediment Contamination: An International Journal* 27 (8): 748–55. https://doi.org/10.1080/15320383.2018.1517726.

McKeever, Robert, Diane Sheppard, Klaus Nüsslein, et al. 2012. "Biodegradation of Ethylene Dibromide (1,2-Dibromoethane [EDB]) in Microcosms Simulating *in Situ* and Biostimulated Conditions." *Journal of Hazardous Materials* 209–210 (March): 92–98. https://doi.org/10.1016/j.jhazmat.2011.12.067.

MDE. 2019. "Technical Guidelines for Vapor Intrusion." Maryland Department of the Environment, September. https://mde.maryland.gov/programs/LAND/MarylandBrownfieldVCP/Documents/VI%20Tech%20combined.pdf.

MDEQ. 2013. "Guidance Document for Vapor Intrusion." Remediation and Redevelopment Division, Michigan Department of Environmental Quality. https://www.michigan.gov/documents/deq/deq-rrd-VIGuidanceDoc-May2013_422550_7.pdf.

MEDEP. 2009. "Maine Department of Environmental Protection Presentation." National UST/LUST/Funds Meeting, Sacramento, CA. https://itrcweb.org/wp-content/uploads/2025/12/2009.04.01-Maine-DEP-Presentation-from-National-Tanks-Conference.pdf.

Michigan EGLE. 2024. *Volume 4: Investigative Approach for Petroleum VIAP 4. Apply a Lateral Screening Distance – Step 2*. Michigan Department of Environment, Great Lakes, and Energy. https://www.michigan.gov/egle/about/organization/remediation-and-redevelopment/vapor-intrusion/guidance/volume-4/apply-a-lateral-screening-distance.

Mills, William B., Sally Liu, Mark C. Rigby, and David Brenner. 2007. "Time-Variable Simulation of Soil Vapor Intrusion into a Building with a Combined Crawl Space and Basement." *Environmental Science & Technology* 41 (14): 4993–5001. https://doi.org/10.1021/es061747d.

Molins, S., and K. U. Mayer. 2007. "Coupling between Geochemical Reactions and Multicomponent Gas and Solute Transport in Unsaturated Media: A Reactive Transport Modeling Study." *Water Resources Research* 43 (5). https://doi.org/10.1029/2006WR005206.

Molins, S., K. U. Mayer, R. T. Amos, and B. A. Bekins. 2010. "Vadose Zone Attenuation of Organic Compounds at a Crude Oil Spill Site — Interactions between Biogeochemical Reactions and Multicomponent Gas Transport." *Journal of Contaminant Hydrology*, Frontiers in Reactive Transport: Microbial Dynamics and Redox Zonation in the Subsurface, vol. 112 (1): 15–29. https://doi.org/10.1016/j.jconhyd.2009.09.002.

Monod, Jacques. 1949. "The Growth of Bacterial Cultures." Pasteur Institute, Paris, France. https://garcialab.berkeley.edu/courses/papers/Monod1949.pdf.

Montana DEQ. 2021. *Montana Vapor Intrusion Guide*. Montana Department of Environmental Quality. https://deq.mt.gov/Files/Land/StateSuperFund/Documents/VI_Guide/MontanaVI_Guide_FINAL.pdf.

Nazaroff, William W. 1992. "Radon Transport from Soil to Air." *Reviews of Geophysics* 30 (2): 137–60. https://doi.org/10.1029/92RG00055.

Nelson, Denice K., Timothy M. LaPara, and Paige J. Novak. 2010. "Effects of Ethanol-Based Fuel Contamination: Microbial Community Changes, Production of Regulated Compounds, and Methane Generation." *Environmental Science & Technology* 44 (12): 4525–30. https://doi.org/10.1021/es903940q.

NFESCA. 2021. *Optimization of Building Pressure Cycling Methods for Vapor Intrusion Studies in Large Buildings*. Naval Facilities Engineering Systems Command Atlantic. https://exwc.navfac.navy.mil/Portals/88/Documents/EXWC/Restoration/er_pdfs/b/BPC%20Optimization%20TM_05_03_21.pdf?ver=DqOWIWCMiAxEcKpzRsnC9g%3D%3D.

NHDES. 2013. *Revised Vapor Intrusion Screening Levels and TCE Update*. New Hampshire Department of Environmental Services. https://www.des.nh.gov/sites/g/files/ehbemt341/files/documents/vapor-intrusion.pdf.

Nicholson, Paul, Darius Mali, and Todd A. McAlary. 2021. "Simplified Approach for Calculating Building-Specific Attenuation Factors and Vapor Intrusion Mitigation System Flux-Based Radius of Influence." *Groundwater Monitoring & Remediation* 41 (2): 122–31. https://doi.org/10.1111/gwmr.12456.

NJDEP. 2005a. *Background Concentrations: Reports on Investigation of Indoor Air Quality in Structures Located Above V0C-Contaminated Groundwater*. For New Jersey Department of Environmental Protection by Golder Associates, Inc.

NJDEP. 2005b. *Report on Year One Soil Vapor Intrusion Research Study at Stafford Township and Egg Harbor Sites, New Jersey.* By Golder Associates Inc. for the New Jersey Department of Environmental Protection. http://hdl.handle.net/10929/25354.

NJDEP. 2013. "Updated Vapor Intrusion Screening Level Tables." Screening Levels: New Jersey Department of Environmental Protection, Site Remediation Program, Vapor Intrusion Guidance, March. http://www.state.nj.us/dep/srp/guidance/vaporintrusion.

NJDEP. 2014. *Quality Assurance Project Plan Technical Guidance. Version 1.0*. New Jersey Department of Environmental Protection Site Remediation Program. https://www.nj.gov/dep/srp/guidance/srra/quality_assurrance_project_plan_guidance.pdf.

NJDEP. 2018. *Vapor Intrusion Technical Guidance, Version 4.1*. New Jersey Department of Environmental Protection. https://www.nj.gov/dep/srp/guidance/vaporintrusion/vit_main.pdf?version_4.1.

NJDEP. 2021. *Vapor Intrusion Technical Guidance. Version 5.0*. New Jersey Department of Environmental Protection Site Remediation and Waste Management Program. https://www.nj.gov/dep/srp/guidance/vaporintrusion/vit_main.pdf.

NJDEP. 2024. "Field Sampling Procedures Manual." *Contaminated Site Remediation & Redevelopment Program*. https://dep.nj.gov/srp/guidance/fspm/.

NYDEC. 2013. *Manufactured Gas Plants*. New York State Department of Environmental Conservation.

NYDEC. 2024. *Gowanus Canal Area-Wide Soil Vapor Intrusion Investigation*. New York State Department of Environmental Conservation. https://extapps.dec.ny.gov/data/der/factsheet/gowanusupdate0824.pdf.

NYSDOH. 2006. "Guidance for Evaluating Soil Vapor Intrusion in the State of New York." New York State Department of Health, October. https://www.health.ny.gov/environmental/indoors/vapor_intrusion/docs/2006_guidance.pdf.

NYSDOH. 2024. "Updates to Soil Vapor/Indoor Air Decision Matrices." February. https://health.ny.gov/environmental/indoors/vapor_intrusion/docs/svi_decision_matrices_def.pdf.

Ohio EPA. 2020. *Sample Collection & Evaluation of Vapor Intrusion to Indoor Air*. Ohio Environmental Protection Agency. https://dam.assets.ohio.gov/image/upload/epa.ohio.gov/Portals/30/vap/docs/VI%20guidance%20Final%203-6-2020.pdf.

Patterson, B. M., R. Aravena, G. B. Davis, A. J. Furness, T. P. Bastow, and D. Bouchard. 2013. "Multiple Lines of Evidence to Demonstrate Vinyl Chloride Aerobic Biodegradation in the Vadose Zone, and Factors Controlling Rates." *Journal of Contaminant Hydrology* 153 (October): 69–77. https://doi.org/10.1016/j.jconhyd.2013.07.008.

Patterson, B. M., and G. B. Davis. 2009. "Quantification of Vapor Intrusion Pathways into a Slab-on-Ground Building under Varying Environmental Conditions." *Environmental Science & Technology* 43 (3): 650–56. https://doi.org/10.1021/es801334x.

Peargin, T., and R. Kolhatkar. 2011. "Empirical Data Supporting Groundwater Benzene Concentration Exclusion Criteria for Petroleum Vapor Intrusion Investigations." International Symposium on Bioremediation and Sustainable Environmental Technologies, Reno, Nevada, June.

Pennell, Kelly G., Ozgur Bozkurt, and Eric M. Suuberg. 2009. "Development and Application of a Three-Dimensional Finite Element Vapor Intrusion Model." *Journal of the Air & Waste Management Association* 59 (4): 447–60. https://doi.org/10.3155/1047-3289.59.4.447.

Picone, Sara, Johan Valstar, Pauline van Gaans, Tim Grotenhuis, and Huub Rijnaarts. 2012. "Sensitivity Analysis on Parameters and Processes Affecting Vapor Intrusion Risk." *Environmental Toxicology and Chemistry* 31 (5): 1042–52. https://doi.org/10.1002/etc.1798.

Plantz, Gina, Kelly Chatterton, Rich Rago, Bart Eklund, Heidi Hayes, and Monica Tran. 2025. "Indoor Air Background Concentrations of Volatile Organic Compounds (VOCs) in California Residences." *Groundwater Monitoring & Remediation* 45 (2): 40–55. https://doi.org/10.1111/gwmr.12719.

Potter, T. L., and K. E. Simmons. 1998. "Composition of Petroleum Mixtures." In *Total Petroleum Hydrocarbon Working Group Series*, vol. 2. Association for Environmental Health and Sciences.

Rago, Richard, Andy Rezendes, Jay Peters, Kelly Chatterton, and Arun Kammari. 2021. "Indoor Air Background Levels of Volatile Organic Compounds and Air-Phase Petroleum Hydrocarbons in Office Buildings and Schools." *Groundwater Monitoring & Remediation* 41 (2): 27–47. https://doi.org/10.1111/gwmr.12433.

Reichman, Rivka, Mohammadyousef Roghani, Evan J. Willett, Elham Shirazi, and Kelly G. Pennell. 2017. "Air Exchange Rates and Alternative Vapor Entry Pathways to Inform Vapor Intrusion Exposure Risk Assessments." *Reviews on Environmental Health* 32 (1–2): 27–33. https://doi.org/10.1515/reveh-2016-0039.

Reichman, Rivka, Elham Shirazi, Donald G. Colliver, and Kelly G. Pennell. 2017. "US Residential Building Air Exchange Rates: New Perspectives to Improve Decision Making at Vapor Intrusion Sites." *Environmental Science: Processes & Impacts* 19 (2): 87–100. https://doi.org/10.1039/C6EM00504G.

Ridge Nation Laboratory (ORNL). 2025. "Risk Assessment Information System (RAIS) Toxicity Values and Physical Parameters Search." https://rais.ornl.gov/cgi-bin/tools/TOX_search?select=chemtox.

Ririe, G. T., R. E. Sweeney, S. J. Daugherty, and P. M. Peuron. 1998. "A Vapor Transport Model That Is Consistent with Field and Laboratory Data." 299–308.

Robinson, Allen L., Richard G. Sextro, and William J. Fisk. 1997. "Soil-Gas Entry into an Experimental Basement Driven by Atmospheric Pressure Fluctuations—Measurements, Spectral Analysis, and Model Comparison." *Atmospheric Environment* 31 (10): 1477–85. https://doi.org/10.1016/S1352-2310(96)00304-4.

Robinson, N. I. 2003. "Modelling the Migration of VOCs from Soils to Dwelling Interiors." *Proceedings of the Fifth National Workshop on the Assessment of Site Contamination* (Adelaide, Australia). https://www.nepc.gov.au/sites/default/files/2022-09/asc-wkshoppaper-04-tphs-robinson-migration-vocs-200301.pdf.

Robinson, N. I., and L. Turczynowicz. 2005. "One- and Three-Dimensional Soil Transportation Models for Volatiles Migrating from Soils to House Interiors." *Transport in Porous Media* 59 (3): 301–23. https://doi.org/10.1007/s11242-004-2554-4.

Roggemans, S., C. L. Bruce, P. C. Johnson, and R. L. Johnson. 2001. "Vadose Zone Natural Attenuation of Hydrocarbon Vapors: An Empirical Assessment of Soil Gas Vertical Profile Data." American Petroleum Institute. https://www.api.org/~/media/files/ehs/clean_water/bulletins/15_bull.pdf.

Rose, Arthur W., Adam R. Hutter, and John W. Washington. 1990. "Sampling Variability of Radon in Soil Gases." *Journal of Geochemical Exploration* 38 (1): 173–91. https://doi.org/10.1016/0375-6742(90)90100-O.

Rossner, Alan, David P. Wick, Ryan F. LeBouf, Christopher Lutes, and Marley Carroll. 2024. "Evaluation of Flow Controllers Used with Evacuated Canisters to Assess VOC Exposures in Occupational and Non-Occupational Environments." *Journal of Occupational and Environmental Hygiene* 21 (7): 504–14. https://doi.org/10.1080/15459624.2024.2345150.

Sander, Rolf. 2023. "Compilation of Henry's Law Constants (Version 5.0.0) for Water as Solvent." *Atmospheric Chemistry and Physics* 23 (19): 10901–2440. https://doi.org/10.5194/acp-23-10901-2023.

Sanders, P. F., and I. Hers. 2006. "Vapor Intrusion in Homes over Gasoline-Contaminated Ground Water in Stafford, New Jersey." *Groundwater Monitoring & Remediation* 26 (1): 63–72. https://doi.org/10.1111/j.1745-6592.2006.00048.x.

Sanders, P. F., I. Hers, and M. Lewis. 2004. "Observed Attenuation Factors Petroleum Hydrocarbon Data: Investigation of Vapor Intrusion in Homes over Petroleum-Contaminated Groundwater in Stafford Township, New Jersey." EPA/AEHS Vapor Intrusion Attenuation Workshop, San Diego, CA.

Sanders, P. F., and A. H. Stern. 1994. "Calculation of Soil Cleanup Criteria for Carcinogenic Volatile Organic Compounds as Controlled by the Soil-to-indoor Air Exposure Pathway." *Environmental Toxicology and Chemistry* 13 (8): 1367–73. https://doi.org/10.1002/etc.5620130818.

Schumacher, Brian A., John H. Zimmerman, R. James Elliot, and Greg R. Swanson. 2016. "The Effect of Equilibration Time and Tubing Material on Soil Gas Measurements." *Soil and Sediment Contamination: An International Journal* 25 (2): 151–63. https://doi.org/10.1080/15320383.2016.1111860.

Schumacher, Brian A., John H. Zimmerman, Alan C. Williams, et al. 2024. "Distribution of Select Per- and Polyfluoroalkyl Substances at a Chemical Manufacturing Plant." *Journal of Hazardous Materials* 464 (February): 133025. https://doi.org/10.1016/j.jhazmat.2023.133025.

Schuver, Henry J., Chris Lutes, Jeff Kurtz, Chase Holton, and Robert S. Truesdale. 2018. "Chlorinated Vapor Intrusion Indicators, Tracers, and Surrogates (ITS): Supplemental Measurements for Minimizing the Number of Chemical Indoor Air Samples—Part 1: Vapor Intrusion Driving Forces and Related Environmental Factors." *Remediation Journal* 28 (3): 7–31. https://doi.org/10.1002/rem.21557.

SFBRWQCB. 2019. *San Francisco Bay Regional Water Quality Control Board Environmental Screening Levels*. San Francisco Bay Regional Water Quality Control Board.

Shen, Rui, Kelly G. Pennell, and Eric M. Suuberg. 2012. "A Numerical Investigation of Vapor Intrusion — The Dynamic Response of Contaminant Vapors to Rainfall Events." *Science of The Total Environment* 437 (October): 110–20. https://doi.org/10.1016/j.scitotenv.2012.07.054.

Shen, Rui, and Eric M. Suuberg. 2016. "Impacts of Changes of Indoor Air Pressure and Air Exchange Rate in Vapor Intrusion Scenarios." *Building and Environment* 96 (February): 178–87. https://doi.org/10.1016/j.buildenv.2015.11.015.

Siegel, Lenny. 2021. "PCE Contamination on Irving Street, San Francisco: What Is Acceptable?" Center for Public Environmental Oversight, September. http://www.cpeo.org/pubs/PCUPCE.pdf.

Sihota, Natasha J., K. Ulrich Mayer, Mark A. Toso, and Joel F. Atwater. 2013. "Methane Emissions and Contaminant Degradation Rates at Sites Affected by Accidental Releases of Denatured Fuel-Grade Ethanol." *Journal of Contaminant Hydrology* 151 (August): 1–15. https://doi.org/10.1016/j.jconhyd.2013.03.008.

Spence, L., and T. Walden. 2011a. "RISC — Risk Integrated Software for Cleanups, RISC Manual Version 5 - RISC5."

Spence, L., and T. Walden. 2011b. "RISC5 Human Health and Ecological Risk Assessment for Contaminated Sites Software." GroundwaterSoftware.Com. https://www.groundwatersoftware.com/risc5.htm.

Strauss, P., and Lenny Siegel. 2010. "Community Guide to Long-Term Management, Mott Haven Campus, Bronx, New York." Center for Public Environmental Oversight, June.

Suuberg, E. M. 2020. *Tools for Understanding Transients in Vapor Intrusion*. Department of Defense Environmental Security Technology Certification Program (ESTCP). https://apps.dtic.mil/sti/trecms/pdf/AD1154459.pdf.

Tennessee DEC. 2023. "Vapor Mitigation Guidance for Sites Enrolled in the Brownfield Projects Voluntary Cleanup Oversight and Assistance Program." Tennessee Department of Environment and Conservation Division of Remediation. https://www.tn.gov/content/dam/tn/environment/remediation/documents/vapor/rem_voap-vm-guide.pdf.

Thiele, E. W. 1939. "Relation between Catalytic Activity and Size of Particle." *Industrial & Engineering Chemistry* 31 (7): 916–20. https://doi.org/10.1021/ie50355a027.

Tillman, Fred, and J. Weaver. 2007. "Temporal Moisture Content Variability beneath and External to a Building and the Potential Effects on Vapor Intrusion Risk Assessment." *Science of the Total Environment* 379 (1): 1–15.

Tittarelli, F. 2009. "Oxygen Diffusion through Hydrophobic Cement-Based Materials." *Cement and Concrete Research* 39 (10): 924–28. https://doi.org/10.1016/j.cemconres.2009.06.021.

Tsuda, R. 2009. "City Permit Process for MEW Projects." City of Mountain View Memorandum, November 6. http://www.cpeo.org/pubs/MV-VIPolicy.pdf.

Turczynowicz, Leonid, and Neville Robinson. 2001. "A Model to Derive Soil Criteria for Benzene Migrating from Soil to Dwelling Interior in Homes with Crawl Spaces." *Human and Ecological Risk Assessment: An International Journal* 7 (2): 387–415. https://doi.org/10.1080/20018091094420.

USDOD. 2009. *DoD Vapor Intrusion Handbook*. Tri-Service Environmental Risk Assessment Workgroup. U.S. Department of Defense. https://clu-in.org/download/char/dodvihdbk200901.pdf.

USDOD. 2017. *Determining the Influence of Background Sources on Indoor Air Concentrations in Vapor Intrusion Assessment*. Tri-Service Environmental Risk Assessment Work Group (TSERAWG).

USEPA. 1986. "RCRA Facility Assessment Guidance." October. https://www.epa.gov/sites/default/files/2016-01/documents/rfaguid.pdf.

USEPA. 1989. *Risk Assessment Guidance (RAGS) for Superfund, Part A*. United States Environmental Protection Agency.

USEPA. 1990. *National Oil and Hazardous Substances Pollution Contingency Plan (40 Code of Federal Regulations (CFR) Part 300)*. United States Environmental Protection Agency.

USEPA. 1991. *Role of the Baseline Risk Assessment in Superfund Remedy Selection Decisions*. United States Environmental Protection Agency. https://www.epa.gov/sites/default/files/2015-11/documents/baseline.pdf.

USEPA. 1992. *Supplemental Guidance to RAGS: Calculating the Concentration Term*. United States Environmental Protection Agency. https://semspub.epa.gov/work/HQ/127549.pdf.

USEPA. 1993a. *Behavior and Determination of Volatile Organic Compounds in Soil: A Literature Review*. United States Environmental Protection Agency.

USEPA. 1993b. *Radon Reduction Techniques for Existing Detached Houses, Technical Guidance (Third Edition) for Active Soil Depressurization Systems*. United States Environmental Protection Agency. https://www.wbdg.org/FFC/EPA/EPACRIT/epa625_r_93_011.pdf.

USEPA. 1994. *Methods for Derivation of Inhalation Reference Concentrations and Application of Inhalation Dosimetry*. United States Environmental Protection Agency. https://www.epa.gov/sites/default/files/2014-11/documents/rfc_methodology.pdf.

USEPA. 1995. *Presumptive Remedies for Soils, Sediments, and Sludges at Wood Treater Sites*. U.S. Environmental Protection Agency Office of Solid Waste and Emergency Response. https://semspub.epa.gov/work/HQ/174929.pdf.

USEPA. 1997. *Health Effects Assessment Summary Tables (HEAST)*. United States Environmental Protection Agency.

USEPA. 2002a. *Ground-Water Sampling Guidelines for Superfund and RCRA Project Managers*. United States Environmental Protection Agency. https://www.epa.gov/sites/default/files/2015-06/documents/gw_sampling_guide.pdf.

USEPA. 2002b. *Ground-Water Sampling Guidelines for Superfund and RCRA Project Managers. Ground Water Forum Issue Paper*. U.S. Environmental Protection Agency Office of Solid Waste and Emergency Response.

USEPA. 2002c. *OSWER Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Solid (Subsurface Vapor Intrusion Guidance)*. United States Environmental Protection Agency. https://nepis.epa.gov/Exe/ZyNET.exe/P1008OTB.TXT?ZyActionD=ZyDocument&Client=EPA&Index=2000+Thru+2005&Docs=&Query=&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A%5Czyfiles%5CIndex%20Data%5C00thru05%5CTxt%5C00000025%5CP1008OTB.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h%7C-

&MaximumDocuments=1&FuzzyDegree=0&ImageQuality=r75g8/r75g8/x150y150g16/i425&Display=hpfr&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=1&SeekPage=x&ZyPURL.

USEPA. 2002d. *Supplemental Guidance for Developing Soil Screening Levels for Superfund Sites*. United States Environmental Protection Agency. https://nepis.epa.gov/Exe/ZyPDF.cgi/91003IJK.PDF?Dockey=91003IJK.PDF.

USEPA. 2004. *User's Guide for Evaluating Subsurface Vapor Intrusion into Buildings*. United States Environmental Protection Agency Office of Emergency and Remedial Response. https://www.epa.gov/sites/default/files/2015-11/documents/2004_0222_3phase_users_guide.pdf.

USEPA. 2006a. *Assessment of Vapor Intrusion in Homes Near the Raymark Superfund Site Using Basement and Sub-Slab Air Samples*. United States Environmental Protection Agency. https://nepis.epa.gov/Exe/ZyNET.exe/2000D268.TXT?ZyActionD=ZyDocument&Client=EPA&Index=2000+Thru+2005&Docs=&Query=&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A%5Czyfiles%5CIndex%20Data%5C00thru05%5CTxt%5C00000009%5C2000D268.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h%7C-&MaximumDocuments=1&FuzzyDegree=0&ImageQuality=r75g8/r75g8/x150y150g16/i425&Display=hpfr&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=1&SeekPage=x&ZyPURL.

USEPA. 2006b. *Comparison of Geoprobe PRT and AMS GVP Soil-Gas Sampling Systems with Dedicated Vapor Probes in Sandy Soils at the Raymark Superfund Site*. United States Environmental Protection Agency. https://nepis.epa.gov/Exe/ZyNET.exe/P1001HNK.TXT?ZyActionD=ZyDocument&Client=EPA&Index=2006+Thru+2010&Docs=&Query=&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A%5Czyfiles%5CIndex%20Data%5C06thru10%5CTxt%5C00000004%5CP1001HNK.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h%7C-&MaximumDocuments=1&FuzzyDegree=0&ImageQuality=r75g8/r75g8/x150y150g16/i425&Display=hpfr&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=1&SeekPage=x&ZyPURL.

USEPA. 2006c. *Guidance on Systematic Planning Using the Data Quality Objectives Process*. United States Environmental Protection Agency. https://www.epa.gov/sites/default/files/2015-06/documents/g4-final.pdf.

USEPA. 2007. *Final Project Report for the Development of an Active Soil Gas Sampling Method*. United States Environmental Protection Agency.

USEPA. 2008. *Brownfields Technology Primer: Vapor Intrusion Considerations for Redevelopment*. United States Environmental Protection Agency.

USEPA. 2009. *Risk Assessment Guidance for Superfund (RAGS), Volume I: Human Health Evaluation Manual (Part F, Supplemental Guidance for Inhalation Risk Assessment)*. United States Environmental Protection Agency.

USEPA. 2010. *Temporal Variation of VOCs in Soils from Groundwater to the Surface/Subslab*. United States Environmental Protection Agency.

USEPA. 2011a. *Background Indoor Air Concentrations of Volatile Organic Compounds in North American Residences (1990–2005): A Compilation of Statistics for Assessing Vapor Intrusion*. United States Environmental Protection Agency. https://www.epa.gov/sites/default/files/2015-09/documents/oswer-vapor-intrusion-background-report-062411.pdf.

USEPA. 2011b. *Third Five-Year Review Report. Cabot Carbon/Koppers Superfund Site Gainesville, Alachua County, Florida*. United States Environmental Protection Agency.

USEPA. 2012a. *Conceptual Model Scenarios for the Vapor Intrusion Pathway*. U.S. Environmental Protection Agency Office of Solid Waste and Emergency Response. https://www.epa.gov/sites/default/files/2015-09/documents/vi-cms-v11final-2-24-2012.pdf.

USEPA. 2012b. *EPA's Vapor Intrusion Database: Evaluation and Characterization of Attenuation Factors for Chlorinated Volatile Organic Compounds and Residential Buildings*. United States Environmental Protection Agency. https://www.epa.gov/sites/default/files/2015-09/documents/oswer_2010_database_report_03-16-2012_final_witherratum_508.pdf.

USEPA. 2012c. *Fluctuation of Indoor Radon and VOC Concentrations Due to Seasonal Variations*. U.S. Environmental Protection Agency Office of Research and Development. https://www.clu-in.org/download/contaminantfocus/vi/VI-EPA600-R-09-073.pdf.

USEPA. 2012d. *National Strategy to Expand Superfund Optimization Practices from Site Assessment to Site Completion*. United States Environmental Protection Agency. https://www.cluin.org/download/REMED/hyopt/Final-National-Strategy.pdf.

USEPA. 2012e. *Petroleum Hydrocarbons And Chlorinated Hydrocarbons Differ In Their Potential For Vapor Intrusion*. United States Environmental Protection Agency. https://www.epa.gov/sites/default/files/2014-09/documents/pvicvi.pdf.

USEPA. 2013a. *3-D Modeling Of Aerobic Biodegradation Of Petroleum Vapors: Effect Of Building Area Size On Oxygen Concentration Below The Slab*. U.S. Environmental Protection Agency Office of Underground Storage Tanks. https://www.epa.gov/sites/default/files/2014-09/documents/building-size-modeling.pdf.

USEPA. 2013b. "EPA History: Love Canal." Collections and Lists. January 29. https://www.epa.gov/history/epa-history-love-canal.

USEPA. 2013c. *Evaluation Of Empirical Data To Support Soil Vapor Intrusion Screening Criteria For Petroleum Hydrocarbon Compounds*. EPA 510-R-13-001. United States Environmental Protection Agency. https://www.epa.gov/sites/default/files/2014-09/documents/pvi_database_report.pdf.

USEPA. 2014a. *Challenges in Bulk Soil Sampling and Analysis for Vapor Intrusion Screening of Soil*. United States Environmental Protection Agency. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100NDQL.txt.

USEPA. 2014b. "Contaminated Site Cleanup Information (CLU-IN). Dense Nonaqueous Phase Liquids (Dnapls). Chemistry and Behavior." https://www.clu-in.org/contaminantfocus/default.focus/sec/dense_nonaqueous_phase_liquids_(dnapls)/cat/Chemistry_and_Behavior/p/6/n/2.

USEPA. 2014c. *EPA Region 9 Response Action Levels and Recommendations to Address Near-Term Inhalation Exposures to TCE in Air from Subsurface Vapor Intrusion Memo*. Region 9 Superfund Division Staff and Management. https://semspub.epa.gov/work/05/928381.pdf.

USEPA. 2014d. *Passive Samplers for Investigations of Air Quality: Method Description, Implementation, and Comparison to Alternative Sampling Methods*. United States Environmental Protection Agency.

USEPA. 2014e. *Sampling and Analysis Plan Guidance and Template*. R9QA/009.1. Version 4, General Projects. United States Environmental Protection Agency. https://www.epa.gov/sites/default/files/2021-03/documents/sap-general.pdf.

USEPA. 2015a. *OSWER Technical Guide for Assessing and Mitigating the Vapor Intrusion Pathway from Subsurface Vapor Sources to Indoor Air*. U.S. Environmental Protection Agency Office of Solid Waste and Emergency Response. https://www.epa.gov/sites/default/files/2015-09/documents/oswer-vapor-intrusion-technical-guide-final.pdf.

USEPA. 2015b. *Risk Assessment Guidance for Superfund (RAGS): Part A*. Reports and Assessments. United States Environmental Protection Agency. https://www.epa.gov/risk/risk-assessment-guidance-superfund-rags-part.

USEPA. 2015c. *Technical Guide for Assessing and Mitigating the Vapor Intrusion Pathway from Subsurface Vapor Sources to Indoor Air*. U.S. Environmental Protection Agency Office of Solid Waste and Emergency Response. https://www.epa.gov/sites/production/files/2015-09/documents/oswer-vapor-intrusion-technical-guide-final.pdf.

USEPA. 2015d. "What Is Vapor Intrusion?" Overviews and Factsheets. September 23. https://www.epa.gov/vaporintrusion/what-vapor-intrusion.

USEPA. 2016. *Petroleum Vapor Intrusion Modeling Assessment with PVIScreen*. United States Environmental Protection Agency. https://nepis.epa.gov/Exe/ZyPDF.cgi/P100TJ1S.PDF?Dockey=P100TJ1S.PDF.

USEPA. 2017a. *Documentation for EPA's Implementation of the Johnson and Ettinger Model to Evaluate Site Specific Vapor Intrusion into Buildings Version 6.0*. Office of Superfund Remediation and Technology Innovation. https://semspub.epa.gov/work/HQ/100000489.pdf.

USEPA. 2017b. *Johnson and Ettinger Model User's Guide*. United States Environmental Protection Agency. https://www.epa.gov/vaporintrusion/epa-spreadsheet-modeling-subsurface-vapor-intrusion#model.

USEPA. 2017c. "Revised Vapor Intrusion Risk Management Decision Matrix." USEPA Region 7. https://semspub.epa.gov/work/07/30352706.pdf.

USEPA. 2017d. "Screening Level Implementation of the Johnson and Ettinger Vapor Intrusion Model." EPA On-Line Tools for Site Assessment Calculation. https://www3.epa.gov/ceampubl/learn2model/part-two/onsite/JnE_lite.html.

USEPA. 2018. "PVIScreen." Data and Tools. February 20. https://www.epa.gov/land-research/pviscreen.

USEPA. 2020. "Vapor Intrusion Handbook." https://semspub.epa.gov/work/05/978577.pdf.

USEPA. 2021. *Sub-Slab Soil Vapor Sampling Fact Sheet*. United States Environmental Protection Agency. https://semspub.epa.gov/work/03/2314155.pdf.

USEPA. 2023. *Soil Gas Sampling Operating Procedure*. United States Environmental Protection Agency. https://www.epa.gov/sites/default/files/2015-06/documents/Soil-Gas-Sampling.pdf.

USEPA. 2024a. "Regional Screening Levels (RSLs)." Data and Tools. November 13. https://www.epa.gov/risk/regional-screening-levels-rsls.

USEPA. 2024b. "Vapor Intrusion Screening Level Calculator." Data and Tools. https://www.epa.gov/vaporintrusion/vapor-intrusion-screening-level-calculator.

USEPA. 2024c. "Volatile Organic Compounds' Impact on Indoor Air Quality." Overviews and Factsheets. https://www.epa.gov/indoor-air-quality-iaq/volatile-organic-compounds-impact-indoor-air-quality.

USEPA, ORD. 2022. "ProUCL Software." Data and Tools. https://www.epa.gov/land-research/proucl-software.

USEPA ORD. 2025. "Integrated Risk Information System." Reports and Assessments. https://www.epa.gov/iris.

USEPA OSRTI. 2025. "Hewlett-Packard (620-640 Page Mill Road) Palo Alto, CA." Overviews and Factsheets. https://cumulis.epa.gov/supercpad/SiteProfiles/index.cfm?fuseaction=second.Cleanup&id=0902134#bkground.

USEPA OUST. 2015. *Technical Guide for Addressing Petroleum Vapor Intrusion at Leaking Underground Storage Tank Sites*. U.S. Environmental Protection Agency, Office of Underground Storage Tanks. https://www.epa.gov/sites/default/files/2015-06/documents/pvi-guide-final-6-10-15.pdf.

VADEQ. 2024. *Virginia Unified Risk Assessment Model — VURAM User Guide for Risk Assessors. Version 3.3.0*. Virginia Department of Environmental Quality. https://www.deq.virginia.gov/our-programs/land-waste/land-remediation.

Verginelli, Iason, and Yijun Yao. 2021. "A Review of Recent Vapor Intrusion Modeling Work." *Groundwater Monitoring & Remediation* 41 (2): 138–44. https://doi.org/10.1111/gwmr.12455.

Verginelli, Iason, Yijun Yao, and Eric M. Suuberg. 2016. "An Excel®-Based Visualization Tool of Two-Dimensional Soil Gas Concentration Profiles in Petroleum Vapor Intrusion." *Groundwater Monitoring & Remediation* 36 (2): 94–100. https://doi.org/10.1111/gwmr.12162.

Verginelli, Iason, Yijun Yao, Yue Wang, Jie Ma, and Eric M. Suuberg. 2016. "Estimating the Oxygenated Zone beneath Building Foundations for Petroleum Vapor Intrusion Assessment." *Journal of Hazardous Materials* 312 (July): 84–96. https://doi.org/10.1016/j.jhazmat.2016.03.037.

Vroblesky, Don. 2001. "User's Guide for Polyethylene-Based Passive Diffusion Bag Samplers to Obtain Volatile Organic Compound Concentrations in Wells. Part I, Deployment, Recovery, Data Interpretation, and Quality Control and Assurance." *Water-Resources Investigations Report*, 2001–4060. https://doi.org/10.3133/wri014060.

Wang, Genfu, Yuting Xiao, Jianping Zuo, et al. 2020. "Physically Simulating the Effect of Lateral Vapor Source-Building Separation on Soil Vapor Intrusion: Influences of Surface Pavements and Soil Heterogeneity." *Journal of Contaminant Hydrology* 235 (November): 103712. https://doi.org/10.1016/j.jconhyd.2020.103712.

Wascom, Daniel. 2007. "A Study of Subsurface Vapor Intrusion from Exploration & Production Waste." Louisiana State University. 10.31390/gradschool_theses.3769, https://repository.lsu.edu/gradschool_theses/3769.

Washington, John W., and Arthur W. Rose. 1992. "Temporal Variability of Radon Concentration in the Interstitial Gas of Soils in Pennsylvania." *Journal of Geophysical Research: Solid Earth* 97 (B6): 9145–59. https://doi.org/10.1029/92JB00479.

WDNR. 2018. *Addressing Vapor Intrusion at Remediation & Redevelopment Sites in Wisconsin*. Wisconsin Department of Natural Resources, Remediation and Redevelopment Program.

WDNR. 2024. "Environmental Cleanup & Brownfields Redevelopment BRRTS on the Web." Wisconsin Department of Natural Resources. https://apps.dnr.wi.gov/botw/GetActivityDetail.do?dsn=263675&siteId=670900&crumb=1.

Weaver, J. W. 2012. "BioVapor Model Evaluation." Pre-Conference Workshop for 23rd National Tanks Conference: New England Interstate Water Pollution Control Commission, St. Louis, MO.

Weaver, J. W. 2013. "PVIScreen." 4th National Tanks Conference and Expo, Denver, CO, September.

Weaver, J. W., and R. V. Davis. 2017. "USEPA's PVI Screen Model for Petroleum Vapor Intrusion." *LUST Line 82*.

Weaver, J. W., and F. D. Tillman. 2005. *Uncertainty and the Johnson-Ettinger Model for Vapor Intrusion Calculations*. United States Environmental Protection Agency. https://nepis.epa.gov/Exe/ZyNET.exe/P1000BEM.TXT?ZyActionD=ZyDocument&Client=EPA&Index=2000+Thru+2005&Docs=&Query=&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A%5Czyfiles%5CIndex%20Data%5C00thru05%5CTxt%5C00000013%5CP1000BEM.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h%7C-&MaximumDocuments=1&FuzzyDegree=0&ImageQuality=r75g8/r75g8/x150y150g16/i425&Display=hpfr&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=1&SeekPage=x&ZyPURL.

Williams, S. 2017. *City of Mountain View Findings Report/Zoning Permit*. City of Mountain View. https://laserfiche.mountainview.gov/WebLink/DocView.aspx?id=268092&dbid=0&repo=CityDocuments&cr=1.

Wilson, J., M. Toso, D. Mackay, N. de Sieyes, and G. DeVaull. 2012. "What's the Deal with Methane at LUST Spill Sites? Part 1." *LUSTLine Bulletin 71*.

Wilson, J., M. Toso, D. Mackay, N. de Sieyes, and G. DeVaull. 2013. "What's the Deal with Methane at LUST Spill Sites? Part 2." *LUSTLine Bulletin 72*.

Winkler, R., F. Ruckerbauer, and K. Bunzl. 2001. "Radon Concentration in Soil Gas: A Comparison of the Variability Resulting from Different Methods, Spatial Heterogeneity and Seasonal Fluctuations." *Science of The Total Environment*, Radon in the Living Environment, vol. 272 (1): 273–82. https://doi.org/10.1016/S0048-9697(01)00704-5.

Wozney, Anne, Ian Hers, Krista Stevenson, Calista Campbell, Nick Nickerson, and Colleen Gosse. 2022. "Multiple Lines of Evidence for Estimating NSZD Rates Overlying a Shallow LNAPL Source Zone." *Groundwater Monitoring & Remediation* 42 (3): 86–104. https://doi.org/10.1111/gwmr.12533.

Yao, Yijun, Fang Mao, Yuting Xiao, Huanyu Chen, Iason Verginelli, and Jian Luo. 2018. "Investigating the Role of Soil Texture in Petroleum Vapor Intrusion." *Journal of Environmental Quality* 47 (5): 1179–85. https://doi.org/10.2134/jeq2018.04.0140.

Yao, Yijun, Fang Mao, Yuting Xiao, and Jian Luo. 2019. "Modeling Capillary Fringe Effect on Petroleum Vapor Intrusion from Groundwater Contamination." *Water Research* 150 (March): 111–19. https://doi.org/10.1016/j.watres.2018.11.038.

Yao, Yijun, Rui Shen, Kelly G. Pennel, and Eric M. Suuberg. 2013. "A Numerical Investigation of Oxygen Concentration Dependence on Biodegradation Rate Laws in Vapor Intrusion." *Environmental Science: Processes & Impacts* 15 (12): 2345–54. https://doi.org/10.1039/C3EM00421J.

Yao, Yijun, Rui Shen, Kelly G. Pennell, and Eric M. Suuberg. 2013a. "A Review of Vapor Intrusion Models." *Environmental Science & Technology* 47 (6): 2457–70. https://doi.org/10.1021/es302714g.

Yao, Yijun, Rui Shen, Kelly G. Pennell, and Eric M. Suuberg. 2013b. "Examination of the Influence of Environmental Factors on Contaminant Vapor Concentration Attenuation Factors Using the U.S. EPA's Vapor Intrusion Database." *Environmental Science & Technology* 47 (2): 906–13. https://doi.org/10.1021/es303441x.

Yao, Yijun, Rui Shen, Kelly G. Pennell, and Eric M. Suuberg. 2013c. "Examination of the U.S. EPA's Vapor Intrusion Database Based on Models." *Environmental Science & Technology* 47 (3): 1425–33. https://doi.org/10.1021/es304546f.

Yao, Yijun, Iason Verginelli, and Eric M. Suuberg. 2016. "A Two-Dimensional Analytical Model of Petroleum Vapor Intrusion." *Water Resources Research* 52 (2): 1528–39. https://doi.org/10.1002/2015WR018320.

Yao, Yijun, Iason Verginelli, and Eric M. Suuberg. 2017. "A Two-Dimensional Analytical Model of Vapor Intrusion Involving Vertical Heterogeneity." *Water Resources Research* 53 (5): 4499–513. https://doi.org/10.1002/2016WR020317.

Yao, Yijun, Yun Wu, Mengling Tang, et al. 2015. "Evaluation of Site-Specific Lateral Inclusion Zone for Vapor Intrusion Based on an Analytical Approach." *Journal of Hazardous Materials* 298 (November): 221–31. https://doi.org/10.1016/j.jhazmat.2015.05.024.

Zimmerman, John H., Christopher Lutes, Brian Cosky, Brian Schumacher, Diane Salkie, and Robert Truesdale. 2017. "Temporary vs. Permanent Sub-Slab Ports: A Comparative Performance Study." *Soil and Sediment Contamination: An International Journal* 26 (3): 294–307. https://doi.org/10.1080/15320383.2017.1298565.

Zimmerman, John H., Alan Williams, Brian Schumacher, et al. 2024. "The Representativeness of Subslab Soil Gas Collection as Effected by Probe Construction and Sampling Methods." *Groundwater Monitoring & Remediation* 44 (3): 106–21. https://doi.org/10.1111/gwmr.12663.

This portion of the page left blank intentionally. Acknowledgements begin on the following page.

APPENDIX A: SUMMARY OF STATE VAPOR INTRUSION PRACTICES

The information presented in this appendix is based on a 2024–2025 survey of U.S. states conducted by the Interstate Technology & Regulatory Council (ITRC). This survey builds upon data previously published by Eklund et al. (2024). All data, when provided, are reported from the information provided by a representative of each state. Where data have not been provided, the cells have been left blank.

ITRC does not endorse or recommend specific values. Instead, it recognizes that each state and regulatory agency determines appropriate values based on their own regulatory framework and requirements.

The survey findings are summarized in the following tables:

- Table A-1. State-Identified Separation Distances
- Table A-2. Available Screening Values and Attenuation Coefficients
- Table A-3. Comparison of Residential Screening Levels for Select Vapor-Forming Chemicals (2025)

The differences observed in Table A-3 can be attributed to a variety of factors, including the following:

- Default assumptions regarding typical or representative building construction parameters used in generic conceptual site models
- Variability in toxicological data, chemical and physical properties, and exposure assumptions used in risk-based equations to derive health-based criteria
- Differences in the allowable risk levels for vapor-forming chemicals
- Consideration of whether a specific vapor-forming chemical is biodegradable

In addition to Tables A-1 through A-3, state-specific information is provided as individual pages. Users can directly access a compilation of Tables A-1 through A-3 and the state-specific information (Appendix A) by visiting **https://itrcweb.org/vapor-intrusion-toolkit/.**

This portion of the page left blank intentionally. The Table A-1 begins on the following page.

Table A-1. State-Identified Separation Distances (2024)

State	Petroleum			Chlorinated	
	Lateral (ft)	Distance Vertical (ft)	LNAPL Vertical (ft)	Lateral (ft)	Vertical (ft)
Alabama					
Alaska	30	4–10	--	100	--
Arizona					
Arkansas					
California	30[A]	10[B]	30	100	100
Colorado	30	5	15	100	--
Connecticut	10	10	--	100	30
Delaware	30	5	15 or 18	100	100
Florida	50	--	--	100	--
Georgia	30	5	15 or 18	100	--
Hawaii	100	15	30	100	--
Idaho	--	5	15	100	100
Illinois					
Indiana	6 (LNAPL = 15)	6	15	100	100
Iowa	500	--	--	--	--
Kansas	30	5	15 or 18	100	40
Kentucky					
Louisiana					
Maine	30	6	15	--	--
Maryland					
Massachusetts	30	15	--	30	15
Michigan	30	5	15	100	--
Minnesota	100	--	--	100	--
Mississippi					
Missouri	100	--	--	100	--
Montana	30	8	15 or 18	100	--
Nebraska	200	--	--	100	100
Nevada	--	--	--	100	100
New Hampshire	30	15	6	100	100
New Jersey	30	30	30	100	100
New Mexico			--	100	--
New York			--	100	--
North Carolina	LNAPL = 100	--	--	100	100
North Dakota			--	100	--
Ohio	30 or 100[C]	6	15	100	--
Oklahoma					
Oregon	30 or 100[D]	--	--	100	--
Pennsylvania	30	5	15	100	--
Rhode Island					
South Carolina	30	5	15		
South Dakota					
Tennessee					
Texas					

Table A-1. State-Identified Separation Distances (2024)

State	Petroleum			Chlorinated	
	Lateral (ft)	Distance Vertical (ft)	LNAPL Vertical (ft)	Lateral (ft)	Vertical (ft)
Utah	30	--	--	100	--
Vermont	30	6	15	100	100
Virginia					
Washington	30	6	15	100	--
West Virginia					
Wisconsin	30	5	15	100	--
Wyoming					

NOTES:

[A]For mixed petroleum/non-petroleum release sites, the 100-foot distance should be used during initial screening (California DTSC 2023)

[B]TPH being under 100 mg/kg (California DTSC 2023)

[C]30 (small sources) or 100

[D]30 (heating oil tank) or 100

SOURCE: California DTSC. 2023. "Supplemental Guidance: Screening and Evaluating Vapor Intrusion." https://dtsc.ca.gov/wp-content/uploads/sites/31/2023/02/VI_SupGuid_Screening-Evaluating.pdf.

Table A-2. Available Screening Values and Attenuation Coefficients

	Types of Generic Screening Values Available								Attenuation Coefficients				
State	Groundwater	Soil	Deep Soil Gas	Shallow Soil Gas / Subslab	Indoor Air	NAPL	Crawl Space	Utilities / Preferential Pathways	Groundwater	Deep Soil Gas	Shallow Soil Gas	Crawl Spaces	Comments
Alabama	X		X	X	X								
Alaska	X			X	X				0.001	0.1	0.1	1	
Arizona	X		X	X	X								
Arkansas													
California	X	X		X	X		X		0.001; not evaluated by OPS	--	0.03	1	
Colorado	X; none for OPS	X; none for OPS		X	X	X	X	X	0.001	0.03	0.03	1	
Connecticut	X			X	X				0.0002	--	0.0013	--	
Delaware	X	X		X					0.001	0.03	0.03	--	
Florida									--	--	0.1	--	
Georgia									0.001	--	0.03	--	Alternative attenuation values allowed
Hawaii									--	--	0.0005	1	
Idaho									0.001	0.03	0.03	--	
Illinois	X			X									
Indiana			x	X	X		X	X	--	0.03	0.03	1	
Iowa	X	X		X									
Kansas									0.001	--	0.03	1	
Kentucky	X		X	X	X								
Louisiana	X		X	X	X								

State	Types of Generic Screening Values Available								Attenuation Coefficients				
	Groundwater	Soil	Deep Soil Gas	Shallow Soil Gas / Subslab	Indoor Air	NAPL	Crawl Space	Utilities / Preferential Pathways	Groundwater	Deep Soil Gas	Shallow Soil Gas	Crawl Spaces	Comments
Maine									0.001	--	0.03	1	
Maryland*	X	X		X	X				0.001	--	0.05	--	
Massachusetts	X			X	X				--	--	0.014	--	
Michigan	X	X		X			X	X	0.001	0.03	0.03	1	
Minnesota				X					--	0.03	0.03	1	
Mississippi													
Missouri	X	X		X	X		X						
Montana	X	X		X	X				0.001	0.03	0.03	1	
Nebraska	X			X	X				0.001		0.03	--	
Nevada	X								0.001				
New Hampshire	X			X	X				0.0001	0.02	0.02	1	
New Jersey	X			X	X				--	--	0.02	--	
New Mexico				X					0.001	--	0.03	--	
New York				X	X				0.001				
North Carolina	X			X	X		X		0.001	--	0.03	1	
North Dakota	X	X		X	X				0.001				
Ohio									0.001	0.03	0.03	1	
Oklahoma													
Oregon	X			X	X				0.001	0.03	0.03	1	
Pennsylvania	X	X	X	X	X				0.0009	0.005	0.026	--	
Rhode Island	X	X							0.001				
South Carolina	X	X				X			NA	NA	NA	NA	NA
South Dakota													
Tennessee	X			X									
Texas					X								
Utah	X		X	X	X								
Vermont	X	X		X	X				0.001	0.03	0.03	1	

	Types of Generic Screening Values Available								Attenuation Coefficients				
State	Groundwater	Soil	Deep Soil Gas	Shallow Soil Gas / Subslab	Indoor Air	NAPL	Crawl Space	Utilities / Preferential Pathways	Groundwater	Deep Soil Gas	Shallow Soil Gas	Crawl Spaces	Comments
Virginia	X	X		X	X	X			0.001	0.01	0.01	--	
Washington	X			X	X		X		0.001			1	
West Virginia	X	X											
Wisconsin	X		X	X	X	X	X	X	0.001	0.01	0.03	1	
Wyoming	X		X	X	X								

NOTES:

OPS = Colorado Division of Oil and Public Safety

Table A-3. Comparison of Residential Screening Levels for Select Vapor-Forming Chemicals (2025)

	Benzene			TCE			PCE			1,1- Dichloroethylene		
State	Groundwater (µg/l)	Soil Gas (µg/m^3)	Indoor Air (µg/m^3)	Groundwater (µg/l)	Soil Gas (µg/m^3)	Indoor Air (µg/m^3)	Groundwater (µg/l)	Soil Gas (µg/m^3)	Indoor Air (µg/m^3)	Groundwater (µg/l)	Soil Gas (µg/m^3)	Indoor Air (µg/m^3)
Alabama	16	120	3.6	5.2	70	2.1	58	1,400	42	196	7,000	210
Alaska	16	36	3.6	5	20	2	58	410	41	200	2,100	79
Arizona	1.6	12	0.36	1.2	16	0.48	15	367	11	196	7,000	210
Arkansas	1.6	12	0.36	1.2	16	0.48	15	367	11	195	7,000	210
California	0.42	3.2	0.097	1.2	16	0.48*	0.64	15	0.46	66	2,400	73
Colorado	1.6	12*	0.36	1.2	16	0.48	15	367	11	195	7,000	210
Connecticut	215	2,500	3.3	27	760	1	340	3,800	5	190	7,600	10
Delaware	1.6	12	0.36	0.52	7	0.21	5.8	140	4.2	19.5	700	21
Florida	--	3.1	0.31	--	--	--	--	--	--	--	--	--
Georgia	15.8	120	3.6	5.2	70	2.1	58	1,400	42	196	7,000	210
Hawaii	2,300	720	0.36	210	830	0.42	190	920	0.46	6,600	83,000	42
Idaho	44	12	0.36	1.2	16	0.48	15	367	11	195	7,000	210
Illinois	110	370	--	340	1,500	--	91	550	--	24,000	240,000	--
Indiana	5	40	4	5	20	2	5	400	40	7	2,000	200
Iowa	1,540	600,000	39.2	--	--	--	--	--	--	--	--	--
Kansas	1.58	120	3.6	5.2	70	2.09	58	1,400	41.7	195	7,000	209
Kentucky	1.59	12	0.36	1.19	15.9	0.478	14.9	360	10.8	195	6,950	209
Louisiana	1.6	12	0.36	1.2	16	0.48	15	367	11	195	7,000	210
Maine	--	120	3.6	--	70	2.1	--	1,400	42	--	7,000	210
Maryland	--	64	3.2	--	42	2.1	--	840	42	--	4,200	210
Massachusetts	1,000	160	2.3	5	28	0.4	20	98	1.4	80	56	0.8
Michigan	14*	110	--	6.2*	67	--	97*	1,400	--	67*	530	--
Minnesota	--	43	1.3	--	70	2.1	--	110	3.4	--	7,000	210
Mississippi	1.6	12	0.36	1.2	16	0.48	15	367	11	195	7,000	210
Missouri	1	190,000	4.98	1600	546,000	12.8	338	200,000	4.27	5,380	446,000	119
Montana	1.6	12	0.36	0.52	7	0.21	5.8	139	4.2	20	700	21
Nebraska	3.1	12	0.36	2.4	16	0.48	32	350	10	83	1,700	52
Nevada	--	--	--	5	--	2.1	50	--	32	--	--	--
New Hampshire	2,900	170	3.3	20	20	0.4	240	400	8	630	2,000	40

	Benzene			TCE			PCE			1,1- Dichloroethylene		
State	Groundwater (µg/l)	Soil Gas (µg/m^3)	Indoor Air (µg/m^3)	Groundwater (µg/l)	Soil Gas (µg/m^3)	Indoor Air (µg/m^3)	Groundwater (µg/l)	Soil Gas (µg/m^3)	Indoor Air (µg/m^3)	Groundwater (µg/l)	Soil Gas (µg/m^3)	Indoor Air (µg/m^3)
New Jersey	23	18	0.64	3	34	1.1	36	540	11	31	1,000	21
New Mexico	15.8	120	3.6	5.16	69.5	2.09	57.5	1,390	41.7	195	6,950	209
New York	--	--	--	--	6	0.2	--	100	3	--	6	0.2
North Carolina	1.6	12	0.36	1	14	0.42	12	280	8.3	39	1,400	42
North Dakota	--	--	--	--	--	--	--	--	--	--	--	--
Ohio	15.9	120	3.6	5.18	69.5	2.1	57.6	1,390	42	195	6,950	210
Oklahoma	15.8	120	3.6	5.2	70	2.1	58	1,390	42	195	7,000	210
Oregon	210	72	0.36	200	95	0.47	3,700	2,200	11	29,000	42,000	210
Pennsylvania	23	120	3.1	9	80	2.1	110	1,600	42	300	8,000	210
Rhode Island	140			540			150					
South Carolina	1.6 (5)	12 (NA)	0.36 (NA)	1.2	16	0.48	15	367	11	195	7,000	210
South Dakota	--	--	--	--	--	--	--	--	--	--	--	--
Tennessee	1.6	12	0.36	0.52	7	0.21	5.8	140	4.2	19.5	700	21
Texas	--	--	11	--	--	2.1	--	--	64	--	--	350
Utah	1.6	12	0.36	1.2	16	0.48	15	367	11	196	7,000	210
Vermont	0.92	4.3	0.13	0.82	6.7	0.2	1.5	21	0.63	270	6,700	200
Virginia	1.6	12	0.36	0.52	7	0.21	5.8	140	4.2	19.7	700	21
Washington	2.4	11	0.321	1.4	11	0.334	25	320	9.6	130	3,000	91.4
West Virginia	1.6	12	0.36	1.2	16	0.48	15	367	11	195	7,000	210
Wisconsin	16	120	3.6	5	70	2.1	5	1,400	42	200	7,000	210
Wyoming	1.6	12	0.36	1.2	16	0.48	15	367	11	196	7,000	210

NOTES: OPS = Colorado Division of Oil and Public Safety

SOURCES: California DTSC. 2014. "Human Health Risk Assessment (HHRA) Note Number 5: Health-Based Indoor Air Screening Criteria for Trichloroethylene (TCE)." https://dtsc.ca.gov/wp-content/uploads/sites/31/2021/07/HHRA-Note-5-23-Aug-2014-2021-A.pdf. CalEPA OEHHA. 2018. "Trichloroethylene (TCE) in Indoor Air." November. https://oehha.ca.gov/sites/default/files/media/downloads/risk-assessment/fact-sheet-california-human-health-screening-levels-chhsls/tceindoorairfactsheet.pdf.

Table A-3. Comparison of Residential Screening Levels for Select Vapor-Forming Chemicals (2025)

	1,1,1- Trichloroethane			
State	**Groundwater (µg/l)**	**Soil Gas (µg/m^3)**	**Indoor Air (µg/m^3)**	**Criteria Notes**
Alabama	7,400	174,000	5,200	
Alaska	7,400	52,000	3,800	
Arizona	7,400	174,000	5,200	
Arkansas	7,400	174,000	5,200	
California	1,500	35,000	1,000	*In accordance with CalEPA/DTSC's HERO Note 5, rapid response concentrations have been established for TCE, including accelerated and urgent action levels of 2 and 6 µg/m³, respectively (California DTSC 2014; CalEPA/OEHHA 2018)
Colorado	7,400	174,000	5,200	*OPS allows 213,000 ug/m^3 for soil gas at 3 feet below floor and within 10 feet of structure, toward source
Connecticut	6,500	380,000	500	
Delaware	740	17,000	520	
Florida	--	--	--	
Georgia	7,400	174,000	5,200	
Hawaii	340,000	2,100,000	1,000	
Idaho	7,400	174,000	5,200	
Illinois	1,000,000	6,600,000	--	
Indiana	200	50,000	5,000	
Iowa	--	--	--	
Kansas	7,400	174,000	5,210	
Kentucky	7,420	174,000	5,210	
Louisiana	7,400	174,000	5,200	
Maine	--	173,333	5,200	
Maryland	--	106,000	5,300	
Massachusetts	4,000	210	3	
Michigan	8,700*	450	--	*Values do not address groundwater in contact
Minnesota	--	7,000	210	
Mississippi	7,400	174,000	5,200	
Missouri	102,000	56,600,000	1,131	
Montana	740	17,000	520	
Nebraska	3,600	43,000	1,300	
Nevada	--	--	--	
New Hampshire	27,000	50,000	1,000	

	1,1,1- Trichloroethane			
State	Groundwater (µg/l)	Soil Gas (µg/m^3)	Indoor Air (µg/m^3)	Criteria Notes
New Jersey	13,000	260,000	5,200	
New Mexico	7,390	174,000	5,210	
New York	--	100	3	
North Carolina	1,500	35,000	1,000	
North Dakota	--	--	--	
Ohio	7,420	174,000	5,200	
Oklahoma	7,400	174,000	5,200	
Oregon	1,290,000	1,000,000	5,200	
Pennsylvania	12,000	200,000	5,200	
Rhode Island	3,100			The residential screening levels are what is currently on the books. New numbers are in draft and in the rule-making process.
South Carolina	7,400	174,000	5,200	Values in "()" are for PVI
South Dakota	--	--	--	
Tennessee	740	17,400	520	
Texas	--	--	5,300	
Utah	7,400	174,000	5,200	
Vermont	7,420	174,000	5,200	
Virginia	739	17,300	520	
Washington	5,400	76,000	2,290	
West Virginia	7,400	174,000	5,200	
Wisconsin	7,400	170,000	5,200	
Wyoming	7,400	174,000	5,200	

NOTES: OPS = Colorado Division of Oil and Public Safety

SOURCES: California DTSC. 2014. “Human Health Risk Assessment (HHRA) Note Number 5: Health-Based Indoor Air Screening Criteria for Trichloroethylene (TCE).” https://dtsc.ca.gov/wp-content/uploads/sites/31/2021/07/HHRA-Note-5-23-Aug-2014-2021-A.pdf. CalEPA OEHHA. 2018. “Trichloroethylene (TCE) in Indoor Air.” November. https://oehha.ca.gov/sites/default/files/media/downloads/risk-assessment/fact-sheet-californiahuman-health-screening-levels-chhsls/tceindoorairfactsheet.pdf.

State	Alabama	Last Updated:	8/27/2025
Agency	Alabama Department of Environmental Management	Abbreviation:	ADEM
Main Webpage	https://adem.alabama.gov/		

Guidance Document (if available) Year:	2025

	Specific Guidance Type			Specific Guidance Type
	Chlorinated Vapor Intrusion Guidance		X	Mitigation
	Petroleum Vapor Intrusion Guidance			Public Stakeholder Document

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	No

Identified Separation Distances (in ft)				
Petroleum			Chlorinated or Other	
Lateral	Dissolved Groundwater Vertical	Nonaqueous Phase Liquid	Lateral	Vertical

Published risk-based target/screening levels for VI in various media available?					
	X	Groundwater		X	Indoor air
		Soil			NAPL
	X	Deep soil gas			Crawl space
	X	Shallow soil gas			Utilities/conduits

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Stepwise approach using both

Number of VOC screening levels available:	VISLs
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	No
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	Deep Soil Gas	Shallow Soil Gas	Crawl Space	Utilities/Conduits
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	No
Recommend number of sampling points in guidance?	Yes
Does your state have a mechanism for long-term monitoring?	Yes
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	Alaska	**Last Updated:**	8/27/2025
Agency	Alaska Department of Environmental Conservation	**Abbreviation:**	ADEC
Main Webpage	https://dec.alaska.gov/		

Guidance Document (if available) Year:	2025

	Specific Guidance Type		Specific Guidance Type
	Chlorinated Vapor Intrusion Guidance	X	Mitigation
	Petroleum Vapor Intrusion Guidance		Public Stakeholder Document

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	0–1 Years

Identified Separation Distances (in ft)				
Petroleum			Chlorinated or Other	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**
30	4–10	--	100	--

Published risk-based target/screening levels for VI in various media available?					
	X	**Groundwater**		X	**Indoor air**
		Soil			**NAPL**
	X	**Deep soil gas**			**Crawl space**
	X	**Shallow soil gas**			**Utilities/conduits**

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Stepwise approach using both

Number of VOC screening levels available:	105
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	No
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
0.001	0.1	0.1	1	
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	Yes
Recommend number of sampling points in guidance?	Yes
Does your state have a mechanism for long-term monitoring?	Yes
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	Vapor barrier should be impermeable to the contaminants of concern
Designer qualification necessary to be met?	

State	Arizona	**Last Updated:**	8/27/2025
Agency	Arizona Department of Environmental Quality	**Abbreviation:**	ADEQ
Main Webpage	https://www.azdeq.gov/		

Guidance Document (if available) Year:	2025

	Specific Guidance Type		Specific Guidance Type
	Chlorinated Vapor Intrusion Guidance	X	**Mitigation**
	Petroleum Vapor Intrusion Guidance		**Public Stakeholder Document**

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	Date not set

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**

Published risk-based target/screening levels for VI in various media available?					
X	**Groundwater**		X	**Indoor air**
	Soil			**NAPL**
X	**Deep soil gas**			**Crawl space**
X	**Shallow soil gas**			**Utilities/conduits**

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Only site-specific

Number of VOC screening levels available:	VISLs
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	No
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**

Notes:

Additional Key Questions	
Recommend number of sampling events in guidance?	No
Recommend number of sampling points in guidance?	No
Does your state have a mechanism for long-term monitoring?	Yes
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	Arkansas	**Last Updated:**	8/27/2025
Agency	Arkansas Department of Energy & Environment	**Abbreviation:**	E&E
Main Webpage	https://ee.arkansas.gov/		

Guidance Document (if available) Year:	2025

	Specific Guidance Type		**Specific Guidance Type**
	Chlorinated Vapor Intrusion Guidance	X	**Mitigation**
	Petroleum Vapor Intrusion Guidance		**Public Stakeholder Document**

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	No

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**

Published risk-based target/screening levels for VI in various media available?					
	Groundwater			**Indoor air**	
	Soil			**NAPL**	
	Deep soil gas			**Crawl space**	
	Shallow soil gas			**Utilities/conduits**	

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Only lookup tables

Number of VOC screening levels available:	RSLs
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	No
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	No
Recommend number of sampling points in guidance?	No
Does your state have a mechanism for long-term monitoring?	No
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	California	**Last Updated:**	8/27/2025
Agency	California Environmental Protection Agency's (Cal/EPA's) Department of Toxic Substances Control (DTSC), State Water Resources Control Board (SWRCB) or the San Francisco or Los Angales Regional Water Quality Control Boards (SFRWQCB or LARWQCB)	**Abbreviation:**	DTSC & State Waterboard or Regional Waterboards
Main Webpage	https://dtsc.ca.gov/vapor-intrusion/ ; https://www.waterboards.ca.gov/water_issues/programs/site_cleanup_program/vapor_intrusion/		

				Guidance Document (if available) Year:	2025
	Specific Guidance Type			**Specific Guidance Type**	
X	**Chlorinated Vapor Intrusion Guidance**		X	**Mitigation**	
	Petroleum Vapor Intrusion Guidance			**Public Stakeholder Document**	

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	NA

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**
30	10	30	100	100

Published risk-based target/screening levels for VI in various media available?					
X	**Groundwater**		X	**Indoor air**	
X	**Soil**			**NAPL**	
X	**Deep soil gas**		X	**Crawl space**	
X	**Shallow soil gas**			**Utilities/conduits**	

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Stepwise approach using both

Number of VOC screening levels available:	69–152
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	Yes
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
001;not evaluated by OP	--	0.03	1	
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	Yes
Recommend number of sampling points in guidance?	No
Does your state have a mechanism for long-term monitoring?	No*
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

*see https://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/sitecleanup/2022_VIM_Guidance.pdf)

State	Colorado	**Last Updated:**	8/27/2025
Agency	Colorado Department of Public Health and Environment; Colorado Division of Oil & Public Safety	**Abbreviation:**	CDPHE; OPS
Main Webpage	https://cdphe.colorado.gov/;https://ops.colorado.gov/		

Guidance Document (if available) Year:	2025

	Specific Guidance Type		Specific Guidance Type
X	**Chlorinated Vapor Intrusion Guidance**	X	**Mitigation**
X	**Petroleum Vapor Intrusion Guidance**		**Public Stakeholder Document**

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	No; (pending 2025 for OPS)

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**
30	5	15	100	--

Published risk-based target/screening levels for VI in various media available?				
X; none for OPS	**Groundwater**		X	**Indoor air**
X; none for OPS	**Soil**		X	**NAPL**
X	**Deep soil gas**		X	**Crawl space**
X	**Shallow soil gas**		X	**Utilities/conduits**

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Stepwise approach using both; OPS uses soil gas if screening distance/factors violated, then sub-slab results, then indoor air as last resort.

Number of VOC screening levels available:	RSLs; OPS: 7
Non-residential criteria available:	No
Option available for site-specific attenuation factors:	No
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
0.001	0.03	0.03	1	
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	No
Recommend number of sampling points in guidance?	No
Does your state have a mechanism for long-term monitoring?	No
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	15–30 depending on sub-slab VOC
Designer qualification necessary to be met?	

State	Connecticut	**Last Updated:**	8/27/2025
Agency	Department of Energy and Environmental Protection	**Abbreviation:**	DEEP
Main Webpage	https://portal.ct.gov/deep		

Guidance Document (if available) Year:	2025

	Specific Guidance Type		Specific Guidance Type
	Chlorinated Vapor Intrusion Guidance	X	**Mitigation**
	Petroleum Vapor Intrusion Guidance		**Public Stakeholder Document**

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	No

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**
10	10	--	100	30

Published risk-based target/screening levels for VI in various media available?					
	X	**Groundwater**		X	**Indoor air**
		Soil			**NAPL**
	X	**Deep soil gas**			**Crawl space**
	X	**Shallow soil gas**			**Utilities/conduits**

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Stepwise approach using both

Number of VOC screening levels available:	73
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	Yes
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
0.0002	--	0.0013	--	
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	Yes
Recommend number of sampling points in guidance?	Yes
Does your state have a mechanism for long-term monitoring?	Yes
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	Delaware	**Last Updated:**	8/27/2025
Agency	Department of Natural Resources and Environmental Control	**Abbreviation:**	DNREC
Main Webpage	https://dnrec.delaware.gov/		

Guidance Document (if available) Year:	2025

	Specific Guidance Type		Specific Guidance Type
X	**Chlorinated Vapor Intrusion Guidance**	X	**Mitigation**
X	**Petroleum Vapor Intrusion Guidance**		**Public Stakeholder Document**

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	No

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**
30	5	15 or 18	100	100

Published risk-based target/screening levels for VI in various media available?					
	X	**Groundwater**			**Indoor air**
	X	**Soil**			**NAPL**
	X	**Deep soil gas**			**Crawl space**
	X	**Shallow soil gas**			**Utilities/conduits**

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Stepwise approach using both

Number of VOC screening levels available:	>190
Non-residential criteria available:	No
Option available for site-specific attenuation factors:	No
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
0.001	0.03	0.03	--	
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	No
Recommend number of sampling points in guidance?	Yes
Does your state have a mechanism for long-term monitoring?	Yes
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	Florida	Last Updated:	8/27/2025
Agency	Florida Department of Health	Abbreviation:	
Main Webpage	https://www.floridahealth.gov		

Guidance Document (if available) Year:	2025

	Specific Guidance Type			Specific Guidance Type
	Chlorinated Vapor Intrusion Guidance		X	Mitigation
	Petroleum Vapor Intrusion Guidance			Public Stakeholder Document

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	No

Identified Separation Distances (in ft)				
Petroleum			Chlorinated or Other	
Lateral	Dissolved Groundwater Vertical	Nonaqueous Phase Liquid	Lateral	Vertical
50	--	--	100	--

Published risk-based target/screening levels for VI in various media available?					
	Groundwater			Indoor air	
	Soil			NAPL	
	Deep soil gas			Crawl space	
	Shallow soil gas			Utilities/conduits	

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Only site-specific

Number of VOC screening levels available:	8
Non-residential criteria available:	No
Option available for site-specific attenuation factors:	No
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	Deep Soil Gas	Shallow Soil Gas	Crawl Space	Utilities/Conduits
--	--	0.1	--	

Notes:	

Additional Key Questions	
Recommend number of sampling events in guidance?	No
Recommend number of sampling points in guidance?	No
Does your state have a mechanism for long-term monitoring?	No
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	Georgia	Last Updated:	8/27/2025
Agency	Georgia Environmental Protection Division	Abbreviation:	EPD
Main Webpage	https://epd.georgia.gov/		

Guidance Document (if available) Year:	2025

	Specific Guidance Type		Specific Guidance Type
X	Chlorinated Vapor Intrusion Guidance	X	Mitigation
X	Petroleum Vapor Intrusion Guidance		Public Stakeholder Document

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	

Identified Separation Distances (in ft)				
Petroleum			Chlorinated or Other	
Lateral	Dissolved Groundwater Vertical	Nonaqueous Phase Liquid	Lateral	Vertical
30	5	15 or 18	100	--

Published risk-based target/screening levels for VI in various media available?					
	Groundwater			Indoor air	
	Soil			NAPL	
	Deep soil gas			Crawl space	
	Shallow soil gas			Utilities/conduits	

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Only site-specific

Number of VOC screening levels available:	RSLs
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	Yes
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	Deep Soil Gas	Shallow Soil Gas	Crawl Space	Utilities/Conduits
0.001	--	0.03	--	
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	Yes
Recommend number of sampling points in guidance?	Yes
Does your state have a mechanism for long-term monitoring?	Yes
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	30
Designer qualification necessary to be met?	

State	Hawaii	**Last Updated:**	8/27/2025
Agency	Hawaii Department of Health	**Abbreviation:**	DOH
Main Webpage	https://health.hawaii.gov/		

Guidance Document (if available) Year:	2025

	Specific Guidance Type		Specific Guidance Type
	Chlorinated Vapor Intrusion Guidance	X	**Mitigation**
	Petroleum Vapor Intrusion Guidance		**Public Stakeholder Document**

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**
100	15	30	100	--

Published risk-based target/screening levels for VI in various media available?					
	Groundwater			**Indoor air**	
	Soil			**NAPL**	
	Deep soil gas			**Crawl space**	
	Shallow soil gas			**Utilities/conduits**	

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	

Number of VOC screening levels available:	72
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	No
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
--	--	0.0005	1	

Notes:

Additional Key Questions	
Recommend number of sampling events in guidance?	
Recommend number of sampling points in guidance?	
Does your state have a mechanism for long-term monitoring?	
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	Idaho	**Last Updated:**	8/27/2025
Agency	Idaho Department of Environmental Quality	**Abbreviation:**	IDEQ
Main Webpage	https://www.deq.idaho.gov/		

Guidance Document (if available) Year:	2025

	Specific Guidance Type		**Specific Guidance Type**
	Chlorinated Vapor Intrusion Guidance	X	**Mitigation**
	Petroleum Vapor Intrusion Guidance		**Public Stakeholder Document**

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**
--	5	15	100	100

Published risk-based target/screening levels for VI in various media available?

	Groundwater		**Indoor air**
	Soil		**NAPL**
	Deep soil gas		**Crawl space**
	Shallow soil gas		**Utilities/conduits**

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	

Number of VOC screening levels available:	RSLs
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	No
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
0.001	0.03	0.03	--	
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	
Recommend number of sampling points in guidance?	
Does your state have a mechanism for long-term monitoring?	
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	Illinois	**Last Updated:**	8/27/2025
Agency	Illinois Environmental Protection Agency	**Abbreviation:**	IEPA
Main Webpage	https://epa.illinois.gov/		

Guidance Document (if available) Year:	2025

	Specific Guidance Type		**Specific Guidance Type**
	Chlorinated Vapor Intrusion Guidance	X	**Mitigation**
	Petroleum Vapor Intrusion Guidance		**Public Stakeholder Document**

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	No

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**

Published risk-based target/screening levels for VI in various media available?

X	**Groundwater**		**Indoor air**	
	Soil		**NAPL**	
X	**Deep soil gas**		**Crawl space**	
X	**Shallow soil gas**		**Utilities/conduits**	

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Stepwise approach using both

Number of VOC screening levels available:	59
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	Yes
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**

Notes:

Additional Key Questions	
Recommend number of sampling events in guidance?	No
Recommend number of sampling points in guidance?	No
Does your state have a mechanism for long-term monitoring?	Yes
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	Indiana	**Last Updated:**	8/27/2025
Agency	Indiana Department of Environmental Management	**Abbreviation:**	IDEM
Main Webpage	https://www.in.gov/idem/		

Guidance Document (if available) Year:	2025

	Specific Guidance Type		Specific Guidance Type
x	Chlorinated Vapor Intrusion Guidance	X	Mitigation
X	Petroleum Vapor Intrusion Guidance		Public Stakeholder Document

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	No

Identified Separation Distances (in ft)				
Petroleum			Chlorinated or Other	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**
6 (LNAPL = 15)	6	15	100	100

Published risk-based target/screening levels for VI in various media available?					
	Groundwater		X	**Indoor air**
0	**Soil**			**NAPL**
X	**Deep soil gas**		X	**Crawl space**
X	**Shallow soil gas**		X	**Utilities/conduits**

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Stepwise approach using both

Number of VOC screening levels available:	148
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	Yes
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
--	0.03	0.03	1	
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	Yes
Recommend number of sampling points in guidance?	Yes
Does your state have a mechanism for long-term monitoring?	Yes
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	Iowa	Last Updated:	8/27/2025
Agency	Department of Natural Resources	Abbreviation:	Iowa DNR
Main Webpage	https://www.iowadnr.gov/		

Guidance Document (if available) Year:	2025

	Specific Guidance Type			Specific Guidance Type
	Chlorinated Vapor Intrusion Guidance		X	Mitigation
	Petroleum Vapor Intrusion Guidance			Public Stakeholder Document

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	No

Identified Separation Distances (in ft)				
Petroleum			Chlorinated or Other	
Lateral	Dissolved Groundwater Vertical	Nonaqueous Phase Liquid	Lateral	Vertical
500	--	--	--	--

Published risk-based target/screening levels for VI in various media available?					
	X	Groundwater			Indoor air
	X	Soil			NAPL
	X	Deep soil gas			Crawl space
	X	Shallow soil gas			Utilities/conduits

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Stepwise approach using both

Number of VOC screening levels available:	4
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	No
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	Deep Soil Gas	Shallow Soil Gas	Crawl Space	Utilities/Conduits
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	Yes
Recommend number of sampling points in guidance?	No
Does your state have a mechanism for long-term monitoring?	No
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	Kansas	**Last Updated:**	8/27/2025
Agency	Kansas Department of Health and Environment	**Abbreviation:**	KDHE
Main Webpage	https://www.kdhe.ks.gov/		

			Guidance Document (if available) Year:	2025
	Specific Guidance Type		**Specific Guidance Type**	
X	**Chlorinated Vapor Intrusion Guidance**	X	**Mitigation**	
X	**Petroleum Vapor Intrusion Guidance**		**Public Stakeholder Document**	

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**
30	5	15 or 18	100	40

Published risk-based target/screening levels for VI in various media available?					
	Groundwater			**Indoor air**	
	Soil			**NAPL**	
	Deep soil gas			**Crawl space**	
	Shallow soil gas			**Utilities/conduits**	

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Lookup tables

Number of VOC screening levels available:	73
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	Yes
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
0.001	--	0.03	1	
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	No
Recommend number of sampling points in guidance?	No
Does your state have a mechanism for long-term monitoring?	Yes
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	Kentucky	Last Updated:	8/27/2025
Agency	Kentucky Department for Environmental Protection	Abbreviation:	KYDEP
Main Webpage	https://eec.ky.gov		

Guidance Document (if available) Year:	2025

	Specific Guidance Type			Specific Guidance Type
	Chlorinated Vapor Intrusion Guidance		X	Mitigation
	Petroleum Vapor Intrusion Guidance			Public Stakeholder Document

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	No

Identified Separation Distances (in ft)				
Petroleum			Chlorinated or Other	
Lateral	Dissolved Groundwater Vertical	Nonaqueous Phase Liquid	Lateral	Vertical

Published risk-based target/screening levels for VI in various media available?				
X	Groundwater		X	Indoor air
	Soil			NAPL
X	Deep soil gas			Crawl space
X	Shallow soil gas			Utilities/conduits

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Only lookup tables

Number of VOC screening levels available:	VISLs
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	No
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	Deep Soil Gas	Shallow Soil Gas	Crawl Space	Utilities/Conduits

Notes:	

Additional Key Questions	
Recommend number of sampling events in guidance?	Yes
Recommend number of sampling points in guidance?	Yes
Does your state have a mechanism for long-term monitoring?	Yes
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	Louisiana	**Last Updated:**	8/27/2025
Agency	Louisiana Department of Environmental Quality	**Abbreviation:**	Louisiana DEQ
Main Webpage	https://deq.louisiana.gov/		

Guidance Document (if available) Year:	2025

	Specific Guidance Type		Specific Guidance Type
	Chlorinated Vapor Intrusion Guidance	X	**Mitigation**
	Petroleum Vapor Intrusion Guidance		**Public Stakeholder Document**

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	Date not set

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**

Published risk-based target/screening levels for VI in various media available?					
X	**Groundwater**		X	**Indoor air**
	Soil			**NAPL**
X	**Deep soil gas**			**Crawl space**
X	**Shallow soil gas**			**Utilities/conduits**

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Only site-specific

Number of VOC screening levels available:	VISLs
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	No
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	No
Recommend number of sampling points in guidance?	No
Does your state have a mechanism for long-term monitoring?	No
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	Maine	**Last Updated:**	8/27/2025
Agency	Maine Department of Environmental Protection	**Abbreviation:**	Maine DEP
Main Webpage	https://www.maine.gov/dep/		

Guidance Document (if available) Year:	2025

	Specific Guidance Type		Specific Guidance Type
	Chlorinated Vapor Intrusion Guidance	X	**Mitigation**
	Petroleum Vapor Intrusion Guidance		**Public Stakeholder Document**

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	

Identified Separation Distances (in ft)

Petroleum			Chlorinated or Other	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**
30	6	15	--	--

Published risk-based target/screening levels for VI in various media available?

	Groundwater		**Indoor air**
	Soil		**NAPL**
	Deep soil gas		**Crawl space**
	Shallow soil gas		**Utilities/conduits**

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	

Number of VOC screening levels available:	100
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	No
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance

Groundwater	Deep Soil Gas	Shallow Soil Gas	Crawl Space	Utilities/Conduits
0.001	--	0.03	1	

Notes:

Additional Key Questions	
Recommend number of sampling events in guidance?	
Recommend number of sampling points in guidance?	
Does your state have a mechanism for long-term monitoring?	
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	Maryland*	**Last Updated:**	8/27/2025
Agency	Maryland Department of the Environment	**Abbreviation:**	MDE
Main Webpage	https://mde.maryland.gov		

			Guidance Document (if available) Year:	2025
Specific Guidance Type			**Specific Guidance Type**	
	Chlorinated Vapor Intrusion Guidance	X	**Mitigation**	
	Petroleum Vapor Intrusion Guidance		**Public Stakeholder Document**	

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	No

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**

Published risk-based target/screening levels for VI in various media available?				
X	**Groundwater**	X	**Indoor air**	
X	**Soil**		**NAPL**	
X	**Deep soil gas**		**Crawl space**	
X	**Shallow soil gas**		**Utilities/conduits**	

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Stepwise approach using both

Number of VOC screening levels available:	RSLs
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	Yes
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
0.001	--	0.05	--	
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	No
Recommend number of sampling points in guidance?	No
Does your state have a mechanism for long-term monitoring?	Yes
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	Massachusetts	**Last Updated:**	8/27/2025
Agency	Massachusetts Department of Environmental Protection	**Abbreviation:**	MassDEP
Main Webpage	https://www.mass.gov/orgs/massachusetts-department-of-environmental-protection		

Guidance Document (if available) Year:	2025

	Specific Guidance Type		**Specific Guidance Type**
	Chlorinated Vapor Intrusion Guidance	X	**Mitigation**
	Petroleum Vapor Intrusion Guidance		**Public Stakeholder Document**

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	No

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**
30	15	--	100	100

Published risk-based target/screening levels for VI in various media available?					
	Groundwater			**Indoor air**	
	Soil			**NAPL**	
	Deep soil gas			**Crawl space**	
	Shallow soil gas			**Utilities/conduits**	

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	

Number of VOC screening levels available:	42
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	No
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
--	--	0.014	--	
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	
Recommend number of sampling points in guidance?	
Does your state have a mechanism for long-term monitoring?	
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	Michigan	**Last Updated:**	8/27/2025
Agency	Environment, Great Lakes, and Energy	**Abbreviation:**	EGLE
Main Webpage	https://www.michigan.gov/egle/		

			Guidance Document (if available) Year:	2025
Specific Guidance Type			**Specific Guidance Type**	
X	**Chlorinated Vapor Intrusion Guidance**		X	**Mitigation**
X	**Petroleum Vapor Intrusion Guidance**			**Public Stakeholder Document**

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	0-1 years

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**
30	5	15	100	--

Published risk-based target/screening levels for VI in various media available?				
X	**Groundwater**			**Indoor air**
X	**Soil**			**NAPL**
X	**Deep soil gas**		X	**Crawl space**
X	**Shallow soil gas**		X	**Utilities/conduits**

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Stepwise approach using both

Number of VOC screening levels available:	141
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	Yes
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
0.001	0.03	0.03	1	
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	Yes
Recommend number of sampling points in guidance?	Yes
Does your state have a mechanism for long-term monitoring?	No
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	Depends on liner diffusion coefficient for contaminant
Designer qualification necessary to be met?	

State	Minnesota	Last Updated:	8/27/2025
Agency	Minnesota Pollution Control Agency	Abbreviation:	MPCA
Main Webpage	https://www.pca.state.mn.us/		

Guidance Document (if available) Year:	2025

	Specific Guidance Type		Specific Guidance Type
X	Chlorinated Vapor Intrusion Guidance	X	Mitigation
X	Petroleum Vapor Intrusion Guidance		Public Stakeholder Document

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	No

Identified Separation Distances (in ft)				
Petroleum			Chlorinated or Other	
Lateral	Dissolved Groundwater Vertical	Nonaqueous Phase Liquid	Lateral	Vertical
100	--	--	100	--

Published risk-based target/screening levels for VI in various media available?					
	Groundwater			Indoor air	
	Soil			NAPL	
X	Deep soil gas			Crawl space	
X	Shallow soil gas			Utilities/conduits	

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Only lookup tables

Number of VOC screening levels available:	62
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	Yes
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	Deep Soil Gas	Shallow Soil Gas	Crawl Space	Utilities/Conduits
--	0.03	0.03	1	
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	Yes
Recommend number of sampling points in guidance?	Yes
Does your state have a mechanism for long-term monitoring?	Yes
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	Mississippi	**Last Updated:**	8/27/2025
Agency	Mississippi Department of Environmental Quality	**Abbreviation:**	MDEQ
Main Webpage	https://www.mdeq.ms.gov/		

Guidance Document (if available) Year:	2025

	Specific Guidance Type		Specific Guidance Type
	Chlorinated Vapor Intrusion Guidance	X	**Mitigation**
	Petroleum Vapor Intrusion Guidance		**Public Stakeholder Document**

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**

Published risk-based target/screening levels for VI in various media available?					
	Groundwater			**Indoor air**	
	Soil			**NAPL**	
	Deep soil gas			**Crawl space**	
	Shallow soil gas			**Utilities/conduits**	

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	

Number of VOC screening levels available:	RSLs
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	No
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	
Recommend number of sampling points in guidance?	
Does your state have a mechanism for long-term monitoring?	
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	Missouri	**Last Updated:**	8/27/2025
Agency	Department of Natural Resources, Division of Environmental Quality	**Abbreviation:**	DNR/DEQ
Main Webpage	https://dnr.mo.gov/about-us/division-environmental-quality		

Guidance Document (if available) Year:	2025

	Specific Guidance Type		**Specific Guidance Type**
	Chlorinated Vapor Intrusion Guidance	X	**Mitigation**
	Petroleum Vapor Intrusion Guidance		**Public Stakeholder Document**

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	0–1 years

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**
100	--	--	100	--

Published risk-based target/screening levels for VI in various media available?					
X	**Groundwater**		X	**Indoor air**	
X	**Soil**			**NAPL**	
X	**Deep soil gas**		X	**Crawl space**	
X	**Shallow soil gas**			**Utilities/conduits**	

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Stepwise approach using both

Number of VOC screening levels available:	40
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	No
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	Yes
Recommend number of sampling points in guidance?	Yes
Does your state have a mechanism for long-term monitoring?	Yes
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	Montana	**Last Updated:**	8/27/2025
Agency	Montana Department of Environmental Quality	**Abbreviation:**	DEQ
Main Webpage	https://deq.mt.gov/		

			Guidance Document (if available) Year:	2025
Specific Guidance Type			**Specific Guidance Type**	
	Chlorinated Vapor Intrusion Guidance		X	**Mitigation**
X	**Petroleum Vapor Intrusion Guidance**			**Public Stakeholder Document**

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	No

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**
30	8	15 or 18	100	--

Published risk-based target/screening levels for VI in various media available?				
X	**Groundwater**		X	**Indoor air**
X	**Soil**			**NAPL**
X	**Deep soil gas**			**Crawl space**
X	**Shallow soil gas**			**Utilities/conduits**

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Stepwise approach using both

Number of VOC screening levels available:	RSLs
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	Yes
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
0.001	0.03	0.03	1	
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	No
Recommend number of sampling points in guidance?	No
Does your state have a mechanism for long-term monitoring?	Yes
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	Nebraska	**Last Updated:**	8/27/2025
Agency	Nebraska Department of Environment and Energy	**Abbreviation:**	NDEE
Main Webpage	http://dee.ne.gov/		

Guidance Document (if available) Year:	2025

	Specific Guidance Type		Specific Guidance Type
	Chlorinated Vapor Intrusion Guidance	X	Mitigation
	Petroleum Vapor Intrusion Guidance		Public Stakeholder Document

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	Date not set

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**
200	--	--	100	100

Published risk-based target/screening levels for VI in various media available?

X	**Groundwater**	X	**Indoor air**	
	Soil		**NAPL**	
X	**Deep soil gas**		**Crawl space**	
X	**Shallow soil gas**		**Utilities/conduits**	

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Only lookup tables

Number of VOC screening levels available:	>200
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	Yes
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
0.001		0.03	--	
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	No
Recommend number of sampling points in guidance?	Yes
Does your state have a mechanism for long-term monitoring?	Yes
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	Nevada	**Last Updated:**	8/27/2025
Agency	Nevada Division of Environmental Protection	**Abbreviation:**	NDEP
Main Webpage	https://ndep.nv.gov/		

Guidance Document (if available) Year:	2025

	Specific Guidance Type		Specific Guidance Type
X	**Chlorinated Vapor Intrusion Guidance**	X	**Mitigation**
X	**Petroleum Vapor Intrusion Guidance**		**Public Stakeholder Document**

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	1–2 years

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**
--	--	--	100	100

Published risk-based target/screening levels for VI in various media available?					
X	**Groundwater**			**Indoor air**	
	Soil			**NAPL**	
	Deep soil gas			**Crawl space**	
	Shallow soil gas			**Utilities/conduits**	

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Only lookup tables

Number of VOC screening levels available:	2
Non-residential criteria available:	No
Option available for site-specific attenuation factors:	No
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
0.001				
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	No
Recommend number of sampling points in guidance?	No
Does your state have a mechanism for long-term monitoring?	Yes
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	New Hampshire	**Last Updated:**	8/27/2025
Agency	New Hampshire Department of Environmental Services	**Abbreviation:**	NHDES
Main Webpage	https://www.des.nh.gov/		

Guidance Document (if available) Year:	2025

	Specific Guidance Type
X	**Chlorinated Vapor Intrusion Guidance**
	Petroleum Vapor Intrusion Guidance

	Specific Guidance Type
X	**Mitigation**
	Public Stakeholder Document

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	2026

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**
30	30	--	100	100

Published risk-based target/screening levels for VI in various media available?

X	**Groundwater**	X	**Indoor air**
	Soil		**NAPL**
X	**Deep soil gas**		**Crawl space**
X	**Shallow soil gas**		**Utilities/conduits**

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Stepwise approach using both

Number of VOC screening levels available:	31
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	Yes
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
0.0001	0.02	0.02	1	

Notes:

Additional Key Questions	
Recommend number of sampling events in guidance?	No
Recommend number of sampling points in guidance?	No
Does your state have a mechanism for long-term monitoring?	Yes
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	New Jersey	**Last Updated:**	8/27/2025
Agency	Department of Environmental Protection	**Abbreviation:**	NJDEP
Main Webpage	https://dep.nj.gov/		

Guidance Document (if available) Year:	2025

	Specific Guidance Type		Specific Guidance Type
	Chlorinated Vapor Intrusion Guidance	X	**Mitigation**
	Petroleum Vapor Intrusion Guidance		**Public Stakeholder Document**

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	No

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**
30	30	30	100	100

Published risk-based target/screening levels for VI in various media available?

X	**Groundwater**		X	**Indoor air**	
	Soil			**NAPL**	
X	**Deep soil gas**			**Crawl space**	
X	**Shallow soil gas**			**Utilities/conduits**	

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Only lookup tables

Number of VOC screening levels available:	45
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	Yes
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
--	--	0.02	--	

Notes:

Additional Key Questions	
Recommend number of sampling events in guidance?	Yes
Recommend number of sampling points in guidance?	Yes
Does your state have a mechanism for long-term monitoring?	Yes
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	New Mexico	**Last Updated:**	8/27/2025
Agency	New Mexico Environmental Department	**Abbreviation:**	NMED
Main Webpage	https://www.env.nm.gov/		

Guidance Document (if available) Year:	2025

	Specific Guidance Type		**Specific Guidance Type**
	Chlorinated Vapor Intrusion Guidance	X	**Mitigation**
	Petroleum Vapor Intrusion Guidance		**Public Stakeholder Document**

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	Date not set

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**
		--	100	--

Published risk-based target/screening levels for VI in various media available?					
	Groundwater			**Indoor air**	
	Soil			**NAPL**	
X	**Deep soil gas**			**Crawl space**	
X	**Shallow soil gas**			**Utilities/conduits**	

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Only lookup tables

Number of VOC screening levels available:	118
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	No
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
0.001	--	0.03	--	
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	No
Recommend number of sampling points in guidance?	No
Does your state have a mechanism for long-term monitoring?	No
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	New York	**Last Updated:**	8/27/2025
Agency	Department of Environmental Conservation	**Abbreviation:**	DEC
Main Webpage	https://dec.ny.gov/		

Guidance Document (if available) Year:	2025

	Specific Guidance Type		Specific Guidance Type
X	Chlorinated Vapor Intrusion Guidance	X	Mitigation
X	Petroleum Vapor Intrusion Guidance		Public Stakeholder Document

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	No

Identified Separation Distances (in ft)				
Petroleum			Chlorinated or Other	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**
		--	100	--

Published risk-based target/screening levels for VI in various media available?

	Groundwater		X	Indoor air
	Soil			NAPL
X	Deep soil gas			Crawl space
X	Shallow soil gas			Utilities/conduits

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Stepwise approach using both

Number of VOC screening levels available:	8
Non-residential criteria available:	No
Option available for site-specific attenuation factors:	Yes
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
0.001				
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	Yes
Recommend number of sampling points in guidance?	Yes
Does your state have a mechanism for long-term monitoring?	Yes
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	North Carolina	**Last Updated:**	8/27/2025
Agency	North Carolina Deptartment of Environmental Quality	**Abbreviation:**	NCDEQ
Main Webpage	https://www.deq.nc.gov/		

			Guidance Document (if available) Year:	2025
	Specific Guidance Type		**Specific Guidance Type**	
X	**Chlorinated Vapor Intrusion Guidance**	X	**Mitigation**	
X	**Petroleum Vapor Intrusion Guidance**		**Public Stakeholder Document**	

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	2+ years

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**
LNAPL = 100	--	--	100	100

Published risk-based target/screening levels for VI in various media available?				
X	**Groundwater**	X	**Indoor air**	
	Soil		**NAPL**	
X	**Deep soil gas**	X	**Crawl space**	
X	**Shallow soil gas**		**Utilities/conduits**	

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Stepwise approach using both

Number of VOC screening levels available:	355
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	Yes
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
0.001	--	0.03	1	
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	Yes
Recommend number of sampling points in guidance?	Yes
Does your state have a mechanism for long-term monitoring?	Yes
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	North Dakota	**Last Updated:**	8/27/2025
Agency	North Dakota Department of Environmental Quality	**Abbreviation:**	NDDEQ
Main Webpage	https://deq.nd.gov/		

Guidance Document (if available) Year:	2025

	Specific Guidance Type		Specific Guidance Type
	Chlorinated Vapor Intrusion Guidance	X	**Mitigation**
	Petroleum Vapor Intrusion Guidance		**Public Stakeholder Document**

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	1–2 years

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**
		--	100	--

Published risk-based target/screening levels for VI in various media available?					
X	**Groundwater**		X	**Indoor air**
X	**Soil**			**NAPL**
X	**Deep soil gas**			**Crawl space**
X	**Shallow soil gas**			**Utilities/conduits**

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Only lookup tables

Number of VOC screening levels available:	0
Non-residential criteria available:	No
Option available for site-specific attenuation factors:	Yes
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
0.001				
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	No
Recommend number of sampling points in guidance?	No
Does your state have a mechanism for long-term monitoring?	Yes
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	Ohio	Last Updated:	8/27/2025
Agency	Ohio Environmental Protection Agency	Abbreviation:	Ohio EPA
Main Webpage	https://epa.ohio.gov/home		

Guidance Document (if available) Year:	2025

	Specific Guidance Type		Specific Guidance Type
	Chlorinated Vapor Intrusion Guidance	X	Mitigation
X	Petroleum Vapor Intrusion Guidance		Public Stakeholder Document

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	No

Identified Separation Distances (in ft)				
Petroleum			Chlorinated or Other	
Lateral	Dissolved Groundwater Vertical	Nonaqueous Phase Liquid	Lateral	Vertical
30 (small sources) or 100	6	15	100	--

Published risk-based target/screening levels for VI in various media available?				
	Groundwater		Indoor air	
	Soil		NAPL	
	Deep soil gas		Crawl space	
	Shallow soil gas		Utilities/conduits	

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Stepwise approach using both

Number of VOC screening levels available:	83
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	No
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	Deep Soil Gas	Shallow Soil Gas	Crawl Space	Utilities/Conduits
0.001	0.03	0.03	1	

Notes:	

Additional Key Questions	
Recommend number of sampling events in guidance?	Yes
Recommend number of sampling points in guidance?	Yes
Does your state have a mechanism for long-term monitoring?	Yes
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	Oklahoma	**Last Updated:**	8/27/2025
Agency	Oklahoma Department of Environmental Quality	**Abbreviation:**	OKDEQ
Main Webpage	https://www.deq.ok.gov/		

Guidance Document (if available) Year:	2025

	Specific Guidance Type		**Specific Guidance Type**
	Chlorinated Vapor Intrusion Guidance	X	**Mitigation**
	Petroleum Vapor Intrusion Guidance		**Public Stakeholder Document**

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	No

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**

Published risk-based target/screening levels for VI in various media available?					
	Groundwater			**Indoor air**	
	Soil			**NAPL**	
	Deep soil gas			**Crawl space**	
	Shallow soil gas			**Utilities/conduits**	

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Stepwise approach using both

Number of VOC screening levels available:	RSLs
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	No
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**

Notes:	

Additional Key Questions	
Recommend number of sampling events in guidance?	No
Recommend number of sampling points in guidance?	No
Does your state have a mechanism for long-term monitoring?	Yes
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	Oregon	**Last Updated:**	8/27/2025
Agency	Department of Environmental Quality	**Abbreviation:**	DEQ
Main Webpage	https://www.oregon.gov/DEQ/Pages/index.aspx		

			Guidance Document (if available) Year:	2025
	Specific Guidance Type		**Specific Guidance Type**	
X	**Chlorinated Vapor Intrusion Guidance**	X	**Mitigation**	
X	**Petroleum Vapor Intrusion Guidance**	X	**Public Stakeholder Document**	

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	Yes, March 2025

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**
30	5	15	100	--

Published risk-based target/screening levels for VI in various media available?					
X	**Groundwater**		X	**Indoor air**	
	Soil			**NAPL**	
X	**Deep soil gas**			**Crawl space**	
X	**Shallow soil gas**			**Utilities/conduits**	

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Lookup tables

Number of VOC screening levels available:	>350
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	No
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
0.001	0.03	0.03	1	
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	Yes
Recommend number of sampling points in guidance?	Yes
Does your state have a mechanism for long-term monitoring?	Yes
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	Minimum 30 mil (and adequate composition: low permeability, durable, chemical resistance)
Designer qualification necessary to be met?	

State	Pennsylvania	**Last Updated:**	8/27/2025
Agency	Department of Environmental Protection	**Abbreviation:**	DEP
Main Webpage	https://www.dep.pa.gov/		

Guidance Document (if available) Year:	2025

	Specific Guidance Type		Specific Guidance Type
X	**Chlorinated Vapor Intrusion Guidance**	X	**Mitigation**
X	**Petroleum Vapor Intrusion Guidance**		**Public Stakeholder Document**

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	No

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**
30	5	15	100	--

Published risk-based target/screening levels for VI in various media available?

X	**Groundwater**	X	**Indoor air**
X	**Soil**		**NAPL**
X	**Deep soil gas**		**Crawl space**
X	**Shallow soil gas**		**Utilities/conduits**

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Only lookup tables

Number of VOC screening levels available:	119
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	Yes
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
0.0009	0.005	0.026	--	
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	Yes
Recommend number of sampling points in guidance?	Yes
Does your state have a mechanism for long-term monitoring?	Yes
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	Vapor barriers should be chemically resistant to the COCs present and installed to the manufacturer recommendations
Designer qualification necessary to be met?	

State	Rhode Island	**Last Updated:**	8/27/2025
Agency	Rhode Island, Department of Environmental Management	**Abbreviation:**	RIDEM
Main Webpage	https://dem.ri.gov/		

	Guidance Document (if available) Year:	2025

	Specific Guidance Type		**Specific Guidance Type**
	Chlorinated Vapor Intrusion Guidance	X	**Mitigation**
	Petroleum Vapor Intrusion Guidance		**Public Stakeholder Document**

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	1–2 years

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**

Published risk-based target/screening levels for VI in various media available?				
X	**Groundwater**		**Indoor air**	
X	**Soil**		**NAPL**	
	Deep soil gas		**Crawl space**	
	Shallow soil gas		**Utilities/conduits**	

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Only lookup tables (in draft)

Number of VOC screening levels available:	43
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	No
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
0.001				
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	No
Recommend number of sampling points in guidance?	No
Does your state have a mechanism for long-term monitoring?	Yes
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	South Carolina	**Last Updated:**	8/27/2025
Agency	South Carolina Department of Environmental Services	**Abbreviation:**	SCDES
Main Webpage	https://des.sc.gov/		

Guidance Document (if available) Year:	2025

	Specific Guidance Type		Specific Guidance Type
	Chlorinated Vapor Intrusion Guidance	X	**Mitigation**
	Petroleum Vapor Intrusion Guidance		**Public Stakeholder Document**

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	Date not set

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**
30	5	15		

Published risk-based target/screening levels for VI in various media available?

X	**Groundwater**		**Indoor air**	
X	**Soil**	X	**NAPL**	
	Deep soil gas		**Crawl space**	
	Shallow soil gas		**Utilities/conduits**	

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Stepwise approach using both

Number of VOC screening levels available:	RSLs (8)
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	No
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
NA	NA	NA	NA	
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	No
Recommend number of sampling points in guidance?	No
Does your state have a mechanism for long-term monitoring?	Yes (NA)
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	NA
Designer qualification necessary to be met?	

State	South Dakota	**Last Updated:**	8/27/2025
Agency	South Dakota Department of Agriculture & Natural Resources	**Abbreviation:**	DANR
Main Webpage	https://danr.sd.gov/		

Guidance Document (if available) Year:	2025

	Specific Guidance Type		**Specific Guidance Type**
	Chlorinated Vapor Intrusion Guidance	X	**Mitigation**
	Petroleum Vapor Intrusion Guidance		**Public Stakeholder Document**

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	

Identified Separation Distances (in ft)

Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**

Published risk-based target/screening levels for VI in various media available?

	Groundwater			**Indoor air**	
	Soil			**NAPL**	
	Deep soil gas			**Crawl space**	
	Shallow soil gas			**Utilities/conduits**	

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	

Number of VOC screening levels available:	6
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	No
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance

Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**

Notes:

Additional Key Questions	
Recommend number of sampling events in guidance?	
Recommend number of sampling points in guidance?	
Does your state have a mechanism for long-term monitoring?	
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	Tennessee	**Last Updated:**	8/27/2025
Agency	Tennessee Department of Environment & Conservation	**Abbreviation:**	TDEC
Main Webpage	https://www.tn.gov/environment.html		

			Guidance Document (if available) Year:	2025
Specific Guidance Type			**Specific Guidance Type**	
X	**Chlorinated Vapor Intrusion Guidance**		X	**Mitigation**
	Petroleum Vapor Intrusion Guidance			**Public Stakeholder Document**

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	No

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**

Published risk-based target/screening levels for VI in various media available?				
X	**Groundwater**		**Indoor air**	
X	**Soil**		**NAPL**	
X	**Deep soil gas**		**Crawl space**	
X	**Shallow soil gas**		**Utilities/conduits**	

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Stepwise approach using both

Number of VOC screening levels available:	VISLs
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	No
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	No
Recommend number of sampling points in guidance?	Yes
Does your state have a mechanism for long-term monitoring?	Yes
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	Texas	**Last Updated:**	8/27/2025
Agency	Texas Commission on Environmental Quality	**Abbreviation:**	TCEQ
Main Webpage	https://www.tceq.texas.gov/		

Guidance Document (if available) Year:	2025

	Specific Guidance Type		**Specific Guidance Type**
	Chlorinated Vapor Intrusion Guidance	X	**Mitigation**
	Petroleum Vapor Intrusion Guidance		**Public Stakeholder Document**

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	No

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**

Published risk-based target/screening levels for VI in various media available?					
	Groundwater		X	**Indoor air**	
	Soil			**NAPL**	
	Deep soil gas			**Crawl space**	
	Shallow soil gas			**Utilities/conduits**	

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Only lookup tables

Number of VOC screening levels available:	>300
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	No
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**

Notes:	

Additional Key Questions	
Recommend number of sampling events in guidance?	No
Recommend number of sampling points in guidance?	No
Does your state have a mechanism for long-term monitoring?	Yes
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	Utah	**Last Updated:**	8/27/2025
Agency	Utah Department of Environmental Quality	**Abbreviation:**	Utah DEQ
Main Webpage	https://deq.utah.gov/		

Guidance Document (if available) Year:	2025

	Specific Guidance Type
	Chlorinated Vapor Intrusion Guidance
	Petroleum Vapor Intrusion Guidance

	Specific Guidance Type
X	**Mitigation**
	Public Stakeholder Document

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	No

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**
30	--	--	100	--

Published risk-based target/screening levels for VI in various media available?					
	X	**Groundwater**		X	**Indoor air**
		Soil			**NAPL**
	X	**Deep soil gas**			**Crawl space**
	X	**Shallow soil gas**			**Utilities/conduits**

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	

Number of VOC screening levels available:	VISLs
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	No
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**

Notes:	

Additional Key Questions	
Recommend number of sampling events in guidance?	No
Recommend number of sampling points in guidance?	No
Does your state have a mechanism for long-term monitoring?	No
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	Vermont	**Last Updated:**	8/27/2025
Agency	Agency of Natural Resources Deptartment of Environmental Conservation	**Abbreviation:**	DEC
Main Webpage	https://dec.vermont.gov/		

	Guidance Document (if available) Year:	2025

	Specific Guidance Type
X	**Chlorinated Vapor Intrusion Guidance**
X	**Petroleum Vapor Intrusion Guidance**

	Specific Guidance Type
X	**Mitigation**
	Public Stakeholder Document

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	No

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**
30	6	15	100	100

Published risk-based target/screening levels for VI in various media available?

X	**Groundwater**	X	**Indoor air**
X	**Soil**		**NAPL**
X	**Deep soil gas**		**Crawl space**
X	**Shallow soil gas**		**Utilities/conduits**

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Only lookup tables

Number of VOC screening levels available:	16
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	No
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
0.001	0.03	0.03	1	

Notes:

Additional Key Questions	
Recommend number of sampling events in guidance?	No
Recommend number of sampling points in guidance?	No
Does your state have a mechanism for long-term monitoring?	Yes
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	Virginia	**Last Updated:**	8/27/2025
Agency	Virginia Department Environmental Quality	**Abbreviation:**	VADEQ
Main Webpage	https://www.deq.virginia.gov/		

Guidance Document (if available) Year:	2025

	Specific Guidance Type		Specific Guidance Type
	Chlorinated Vapor Intrusion Guidance	X	**Mitigation**
	Petroleum Vapor Intrusion Guidance		**Public Stakeholder Document**

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	No

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**

Published risk-based target/screening levels for VI in various media available?					
X	**Groundwater**		X	**Indoor air**	
X	**Soil**		X	**NAPL**	
X	**Deep soil gas**			**Crawl space**	
X	**Shallow soil gas**			**Utilities/conduits**	

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Stepwise approach using both

Number of VOC screening levels available:	>300
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	No
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
0.001	0.01	0.01	--	
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	No
Recommend number of sampling points in guidance?	No
Does your state have a mechanism for long-term monitoring?	No
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	Washington	**Last Updated:**	8/27/2025
Agency	Washington State Department of Ecology	**Abbreviation:**	Ecology
Main Webpage	https://ecology.wa.gov/		

			Guidance Document (if available) Year:	2025
	Specific Guidance Type		**Specific Guidance Type**	
X	**Chlorinated Vapor Intrusion Guidance**	X	**Mitigation**	
X	**Petroleum Vapor Intrusion Guidance**		**Public Stakeholder Document**	

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	No

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**
30	6	15	100	--

Published risk-based target/screening levels for VI in various media available?				
X	**Groundwater**	X	**Indoor air**	
	Soil		**NAPL**	
X	**Deep soil gas**	X	**Crawl space**	
X	**Shallow soil gas**		**Utilities/conduits**	

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Only lookup tables

Number of VOC screening levels available:	88
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	No
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
0.001			1	
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	No
Recommend number of sampling points in guidance?	No
Does your state have a mechanism for long-term monitoring?	Yes
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	West Virginia	**Last Updated:**	8/27/2025
Agency	West Virginia Department of Environmental Protection	**Abbreviation:**	DEP
Main Webpage	https://dep.wv.gov/		

Guidance Document (if available) Year:	2025

	Specific Guidance Type		Specific Guidance Type
	Chlorinated Vapor Intrusion Guidance	X	**Mitigation**
	Petroleum Vapor Intrusion Guidance		**Public Stakeholder Document**

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	No

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**

Published risk-based target/screening levels for VI in various media available?

X	**Groundwater**		**Indoor air**	
X	**Soil**		**NAPL**	
	Deep soil gas		**Crawl space**	
	Shallow soil gas		**Utilities/conduits**	

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Stepwise approach using both

Number of VOC screening levels available:	RSLs
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	No
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**

Notes:

Additional Key Questions	
Recommend number of sampling events in guidance?	Yes
Recommend number of sampling points in guidance?	No
Does your state have a mechanism for long-term monitoring?	Yes
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

State	Wisconsin	**Last Updated:**	8/27/2025
Agency	Wisconsin Department of Natural Resources	**Abbreviation:**	WI DNR
Main Webpage	https://dnr.wisconsin.gov/		

			Guidance Document (if available) Year:	2025
	Specific Guidance Type		**Specific Guidance Type**	
X	**Chlorinated Vapor Intrusion Guidance**	X	**Mitigation**	
X	**Petroleum Vapor Intrusion Guidance**		**Public Stakeholder Document**	

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	0–1 years

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**
30	5	15	100	--

Published risk-based target/screening levels for VI in various media available?				
X	**Groundwater**	X	**Indoor air**	
	Soil	X	**NAPL**	
X	**Deep soil gas**	X	**Crawl space**	
X	**Shallow soil gas**	X	**Utilities/conduits**	

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Only lookup tables

Number of VOC screening levels available:	VISLs
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	Yes
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**
0.001	0.01	0.03	1	
Notes:				

Additional Key Questions	
Recommend number of sampling events in guidance?	Yes
Recommend number of sampling points in guidance?	Yes
Does your state have a mechanism for long-term monitoring?	No
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	no specific thickness; use vapor barrier designed for COCs and tested for concentrations at site
Designer qualification necessary to be met?	

State	Wyoming	**Last Updated:**	8/27/2025
Agency	Wyoming Department of Environmental Quality	**Abbreviation:**	Wyoming DEQ
Main Webpage	https://deq.wyoming.gov/		

			Guidance Document (if available) Year:	2025
Specific Guidance Type			**Specific Guidance Type**	
	Chlorinated Vapor Intrusion Guidance	X	**Mitigation**	
	Petroleum Vapor Intrusion Guidance		**Public Stakeholder Document**	

If your state is considering the development or revision of vapor intrusion guidance, what is the timeline for its publication?	1–2 years

Identified Separation Distances (in ft)				
Petroleum			**Chlorinated or Other**	
Lateral	**Dissolved Groundwater Vertical**	**Nonaqueous Phase Liquid**	**Lateral**	**Vertical**

Published risk-based target/screening levels for VI in various media available?					
	X	**Groundwater**		X	**Indoor air**
		Soil			**NAPL**
	X	**Deep soil gas**			**Crawl space**
	X	**Shallow soil gas**			**Utilities/conduits**

Do you have criteria that are generically used (e.g., lookup tables) or is every site site-specific?	Stepwise approach using both

Number of VOC screening levels available:	VISLs
Non-residential criteria available:	Yes
Option available for site-specific attenuation factors:	No
Target cancer risk level:	
Target hazard quotient for potential non-cancer effects:	

Attenuation Values used in Guidance				
Groundwater	**Deep Soil Gas**	**Shallow Soil Gas**	**Crawl Space**	**Utilities/Conduits**

Notes:

Additional Key Questions	
Recommend number of sampling events in guidance?	No
Recommend number of sampling points in guidance?	No
Does your state have a mechanism for long-term monitoring?	Yes
Recommended differential pressure target for active mitigation systems (range or minimum) (Pa)	
Recommended vapor membrane thickness for passive mitigation systems (range or minimum) (mil)	
Designer qualification necessary to be met?	

APPENDIX B: EXAMPLE DOCUMENTS

B.1 Fact Sheets

- EPA General Vapor Intrusion Fact Sheet
- Indiana Vapor Mitigation Fact Sheet
- New Jersey General Vapor Intrusion Fact Sheet
- Maryland Citizens Guide to Vapor Intrusion: LRP—Vapor Intrusion Citizen's Guide Fact Sheet Update September 2019
- Minnesota General Vapor Intrusion Fact Sheet
- Minnesota Department of Health: Your Health and Vapor Intrusion Fact Sheet
- Wisconsin Vapor Intrusion Mitigation Fact Sheet: RR094
- Wisconsin Vapor Intrusion Mitigation Fact Sheet Spanish: RR094a

B.2 Access Agreements

- Wisconsin Access Agreement Template
- USEPA Consent for Access to Property Form

B.3 Building Surveys

- Vermont Initial Building Assessment and Inventory (in Appendix B)
- California Building Survey Form
- Minnesota Vapor Intrusion Building Survey Form

B.4 Instructions for Homeowners Regarding Household Products

- USEPA Household Products Information Sheet (Appendix C)

B.5 Sample Result Reports

- Minnesota Pollution Control Agency: Understanding Your Vapor Intrusion Test Results
- USEPA Region V Sample Report letter (in Appendix G)

APPENDIX C: CHEMISTRY OF PETROLEUM

This appendix provides information about the composition and chemistry of petroleum hydrocarbon (PHC) fuels and their vapors. This information may be used to identify certain petroleum chemicals that pose the greatest potential risks through petroleum vapor intrusion (PVI).

C.1 Aliphatic and Aromatic Compounds

PHCs are generally classified into two main groups: aliphatic and aromatic compounds. Aliphatic compounds are diverse and include straight-chained, branched, and cyclic structures. They can be either saturated, like alkanes, or unsaturated, such as alkenes and alkynes. Aromatic compounds, on the other hand, are characterized by the presence of one or more aromatic rings, often benzene or heterocyclic rings. These rings feature conjugated electrons, meaning the electrons are delocalized or shared across the chemical structure, as is prominently observed in benzene. Some examples of aliphatic and aromatic compounds are shown in **Figure C-1**.

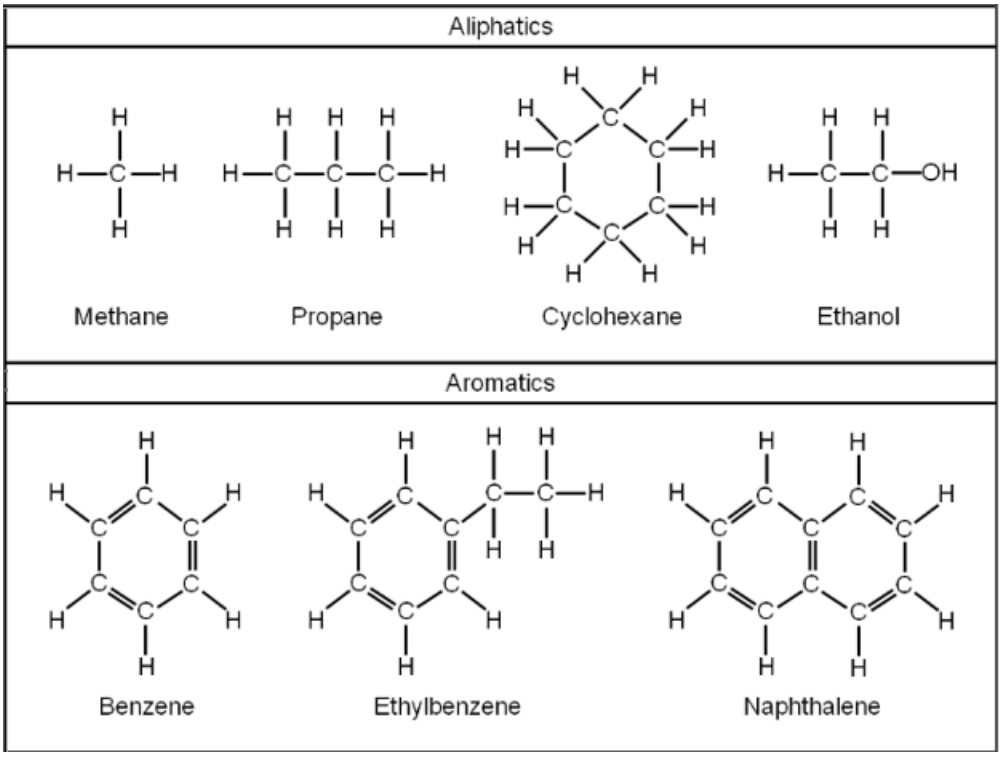


Figure C-1. Examples of aliphatic and aromatic compounds.

In general, aromatic and large aliphatic compounds (C9 and above) are more toxic than smaller aliphatic compounds (under C9); however, smaller aliphatic compounds are more volatile and are, therefore, generally the primary component in vapors if present in the petroleum source. Aromatic compounds are more readily biodegraded than aliphatic compounds; however, a few volatile aromatic compounds, such as benzene and ethylbenzene, and some semivolatile aromatic compounds, such as naphthalene, pose a carcinogenic risk, whereas the aliphatic compounds are generally assumed to pose a noncarcinogenic risk. Although many aliphatic and some aromatic compounds may not be carcinogens, they can collectively pose a noncancer hazard if present at high enough concentrations and should be considered during PVI investigations.

Fuels as well as vapors are characterized in terms of individual compounds and carbon range groups of aliphatic and aromatic compounds. Physicochemical parameter values for PHCs can be found in the Chemical-Specific Parameters Table provided as part of the U.S. Environmental Protection Agency's (USEPA's) *Regional Screening Level Guidance* (USEPA 2024a).

C.2 Petroleum Fuels

Gasolines, *middle distillates*, and *residual fuels* are classifications developed for different mixtures of aliphatic and aromatic compounds. The middle category includes diesel, kerosene, and Stoddard solvent, as defined by the API (1994)

Gasolines are defined as petroleum mixtures characterized by a predominance of branched alkanes with carbon ranges from C2–C12 and lesser amounts of aromatic compounds (such as benzene, toluene, ethylbenzene, and xylenes [collectively known as BTEX]), straight-chain alkanes, cycloalkanes, and alkenes of the same carbon range. Because of the lower molecular weights of these compounds, gasoline has the greatest volatility of the three classes and generally emits the most vapors.

Middle distillates (such as diesel fuel, home heating fuel, kerosene, and jet fuel) are characterized by a wider variety of straight, branched, and cyclic alkanes, as well as polycyclic aromatic hydrocarbons (PAHs) (especially naphthalene and methylnaphthalenes) and heterocyclic compounds with carbon ranges of approximately C5–C9. A small percentage of C8–C25 aliphatic and BTEX compounds are also present in middle distillates. In general, the constituents of middle distillates are less volatile than those of gasolines. Although BTEX compounds are present in middle distillates, their concentrations are several orders of magnitude lower than in gasoline. Naphthalene can also sometimes be considered an aromatic of concern for releases of middle distillates.

Residual fuels (such as fuel oil Nos. 4, 5, and 6; lubricating oils; waste oils; and asphalts) are characterized by complex PAHs and other high-molecular-weight hydrocarbon compounds with carbon ranges that generally fall between C24 and C40. Residual fuels lack a significant amount of volatile compounds and, aside from the potential generation of methane, are generally assumed to pose a minimal vapor intrusion (VI) risk.

Aromatic compounds including BTEX and naphthalene constitute a relatively minor proportion of bulk gasoline and diesel fuel. The remainder of the fuels is composed of hundreds of nonspecific, hydrocarbon compounds, collectively referred to as total petroleum hydrocarbons (TPH).

Fuel additives such as methyl tertiary-butyl ether; ethyl tert-butyl ether; tert-amyl methyl ether, an oxygenate; etc., which have higher Henry's Law constants, can potentially alter the vapor risk that would be posed by the gasoline vapors alone.

Fuels are dominated by aliphatic compounds, although gasolines can contain a relatively large proportion of C9–C12 aromatic compounds. These aromatic compounds are not significantly volatile and, as discussed below, play a relatively minor role in PVI. The same is true of the heavier, relatively low-volatility, C9–C18 aliphatic compounds, although in some cases these compounds can make up an important proportion of vapors emitted from middle distillate fuels. Although they constitute a significant proportion of middle distillates and heavy fuels, aliphatic compounds with 19 or more carbon molecules are not considered volatile and, other than the potential generation of biogenic methane during degradation, do not play a role in PVI.

In addition to gasolines, middle distillates, and residual fuels, other petroleum-related products exhibit potential for PVI, including coal tar, coal tar creosotes, natural gas, and others. Coal tar was created as a by-product of the pyrolysis of coal, coke, or oil in a closed vessel (retort) during production of manufactured gas during the late 1800s to the 1940s (EPRI 1999). Coal tar is a dark reddish brown to

black oily liquid that does not readily mix with water. Coal tar has a strong odor of mothballs or driveway sealer and can be found either as a light nonaqueous-phase liquid or a dense nonaqueous-phase liquid, depending on the formulation process. Coal tar contains a small percentage of vapor-forming chemicals such as BTEX compounds. These compounds are the most soluble in groundwater. Coal tar also contains hundreds of PAHs, which do not readily dissolve in water and are not easily transported in groundwater. Except for naphthalene, most of the PAHs also do not readily volatilize. Coal tar creosotes are distilled from coal tar and contain similar compounds with lesser amounts of the heavier compounds (EPRI 1993).

The class of petroleum product released has a significant effect on what chemicals of concern (COCs) could be present and can be used to determine the presence or absence of PVI. The original composition of the product can vary within the classes and can affect the composition of vapors. The amount of BTEX, naphthalene, other aromatics, and aliphatics can differ based on the refinery producing the fuel and the additives in the formulation of the fuels. For example, in 2011, the USEPA restricted the volume of benzene allowed in gasoline, whether refined or imported, to an average of 0.62% volume through exhaust emissions regulations (Control of Hazardous Air Pollutants From Mobile Sources 2007).

Original fuel formulation and composition has likely varied over time and, along with the effects of weathering, can change the composition significantly; therefore, the composition must be evaluated on a site-by-site basis.

C.3 Petroleum Vapors

The chemical makeup of vapors emitted from petroleum fuels is based on the composition of the fuels and the theoretical partitioning of chemicals released to soil and groundwater (Hartman 1998; USEPA 2002d). Compounds with comparatively higher vapor pressures and Henry's Law coefficients can be expected to dominate vapors relative to their proportions in the parent fuels. Vapors emitted from fresh gasolines can thus be predicted to be dominated by C5–C8 aliphatics (and C2–C4 aliphatics, if present) based both on the relative abundance of these compounds in the parent fuel and on their volatility in comparison to the other compounds. More recent fuels have a lesser amount of benzene because of the increased restriction in the amount of benzene allowed in the fuel; therefore, lower concentrations of benzene in soil vapors can be expected at more recent releases.

Although less volatile than gasolines, diesel and other middle distillate fuels contain variable amounts of C5–C8 aliphatics and a relatively large component of C9–C18 aliphatics. Therefore, these compounds should again be expected to dominate vapors emitted from soil and groundwater contaminated with these fuels. The relative proportion of C5–C8 to C9–C12 aliphatics will depend in part on the original composition of the fuel (Hayes 2007). The fraction of BTEX in the vapors will be significantly smaller than for gasolines, given their lower relative abundance. Naphthalene could also be present, depending on its presence in the parent fuel.

The USEPA Office of Underground Storage Tanks has compiled an empirical database of soil vapor results for more than 50, primarily gasoline-contaminated sites in the U.S., Canada, and Australia (USEPA 2013c). The database provides an overview of the basic chemistry of vapors at gasoline release sites. C5–C8 aliphatics overwhelmingly dominate the TPH fraction in samples that were tested.

The predicted composition of vapors from diesel and other middle distillate fuels is also observed in the field. Mixtures of C5–C12 aliphatics composed the overwhelming majority of vapors at sites contaminated with middle distillate fuels; for more details, see Brewer et al. (2013) and the Hawaii Department of Health (2012).

In summary, vapors from PHC-contaminated soil and groundwater are generally dominated by volatile, aliphatic compounds with lesser but potentially important amounts of benzene and other aromatic

compounds. A detailed discussion of methods to quantitatively assess the VI risk posed by individual compounds or groups of compounds, including TPH aliphatics, is beyond the scope of this document. Brewer et al. (2013) present an approach for the quantitative assessment of TPH in VI studies and the comparison of the risk posed by TPH with that of other COCs.

TPH aliphatics can be the primary COCs when benzene is not present or is depleted. The estimated magnitude of this risk depends in part on the toxicity factors applied to individual TPH carbon ranges. Equally important, VI depends on the ability of the vapors to migrate though the vadose zone and enter a building above levels of potential concern. Field studies indicate that biodegradation of hydrocarbon compounds significantly limits this threat at many if not most sites.

This portion of the page left blank intentionally. The next appendix begins on the following page.

APPENDIX D: COMMON TYPES OF PETROLEUM SITES

Petroleum contamination can occur at various types of sites including industrial, commercial, and residential land use settings. Potential petroleum vapor intrusion (PVI) issues may be different depending on the unique characteristics (such as nature of release or subsurface lithology) of each site. This appendix summarizes different features that may influence the potential for PVI at some commonly encountered petroleum sites. Nine different types of petroleum sites are used as selected examples in this appendix:

- Section D.1: Gasoline Underground Storage Tanks (USTs) and Diesel USTs
- Section D.2: Commercial/Home Heating Oil Tanks
- Section D.3: Refineries
- Section D.4: Bulk Storage Facilities
- Section D.5: Pipelines and Transportation
- Section D.6: Oil Exploration and Production Sites
- Section D.7: Former Manufactured Gas Plants
- Section D.8: Creosote (Wood-Treating) Facilities
- Section D.9: Dry Cleaners Using Petroleum Solvents

The site type examples detailed in this appendix are examples of common petroleum site types and may not cover all site type possibilities or all site-specific scenarios. Components of the sites described in this appendix may be applicable to other types of petroleum sites. In addition, the site types listed in this appendix are scenarios focused on risk from the potential vapor intrusion (VI) pathway and not on other general indoor air quality issues (such as odors) that may result from indoor sources.

The following site features are discussed for each site type:

- History and general description
- Possible compounds and chemicals of concern (COCs)
- Description of potential sources of releases
- Description of contaminant migration and typical receptors
- Description of potential PVI pathway and site-specific limitations to PVI
- Potential for methane generation

The following topics are not addressed in the site descriptions contained in this appendix:

- State or federal regulations or guidance for PVI assessments
- Occupational Safety and Health Administration regulations (may apply but are beyond the scope of this appendix)

- Sites with commingled contaminants (sites where releases of chlorinated and nonchlorinated hydrocarbons occur together)
- Sites closed prior to regulatory consideration of the PVI pathway
- Sites with blended petroleum hydrocarbon (PHC) compounds

For sites with blended PHC compounds, the fate and transport of blended PHC compounds containing more than 10% ethanol may differ from fuels that contain less than 10% ethanol. Additionally, methane may be generated during the ethanol biodegradation. For more information on this topic, refer to **Biofuels: Release Prevention, Environmental Behavior, and Remediation** (ITRC 2011).

Tables D-1 through D-3 provide summaries of the characteristics of each type of site discussed in this appendix. Characteristics used to distinguish each type include the presence of specific indicator compounds, the presence of certain carbon-chain ranges, the potential sources of the release, the relative size of the release, preferential pathways potentially associated with the release source, and key assessment factors. Note that the characteristics summarized in the table are characteristics as they relate to the potential for PVI. For example, the indicator compounds listed in the tables are compounds that may be important in evaluating the potential for PVI. The group of indicator compounds summarized is not an exhaustive list of possible compounds that may be detected on the particular petroleum site type. Also, note that elevated total petroleum hydrocarbons (TPH) values may be an indicator that PVI risk is possible and that it may be necessary to conduct further investigation.

Table D-1. Selected common petroleum site types.

Characteristic	Gasoline and Diesel USTs	Commercial and Home Heating Oil Tanks	Refineries
Common Indicator Compounds	Gasoline: BTEX, naphthalene, methane Diesel: naphthalene, methane Sulfur-free diesel: n-alkanes	Naphthalene, benzene	BTEX, naphthalene, methane
Carbon-Chain Range(s)	C5–C20 Aliphatics C6–C10 Aromatics	No. 2 Fuel: C8–C21 No. 6 Fuel: C8–C30	Various
Potential Release Sources	USTs, product lines, dispensers, service bays	USTs, ASTs, product lines	Underground or aboveground piping, USTs (former and current), ASTs, loading areas, tank pits (current and former), processing units, historical disposal sites
Relative Size	Small to medium	Small to medium (pending site of tank release)	Large
Potential Preferential Pathways	General utilities, karst/-fractured bedrock (location dependent)	Utilities corridor entering building foundation, sumps in basement, cracks in basement floor, karst/fractured bedrock (location dependent)	General utilities, pipeline corridors, karst/fractured bedrock (location dependent)
Key Assessment Factors	Documenting historical and current uses of the site (former UST locations)	Amount of release, distance to the building foundation	Documenting historical and current uses of the site

Note: AST = aboveground storage tank; BTEX = benzene, toluene, ethylbenzene, and xylenes; UST = underground storage tank.

Table D-2. Selected common petroleum site types.

Characteristic	Bulk Storage Facilities	Pipelines/Transportation	Oil Exploration and Production Sites
Common Indicator Compounds	**For oil/petroleum/gasoline:** BTEX, naphthalene, methane	**For oil/petroleum/gasoline:** BTEX, naphthalene, methane **For natural gas:** methane, butane, propane, benzene	BTEX, methane
Carbon-Chain Range(s) Potential Release Sources	Various but most often **Diesel:** C12–C24 **Gasoline:** C4–C12 Underground or aboveground piping, ASTs, oil/water separators, loading areas	Various pipelines, pipe joints, valves, flanges, weld points	Broad range including crude oil and any number of refined products Wells and well area, pipelines, gathering lines, mud pits, USTs (and associated piping), ASTs (and associated piping), maintenance facilities, oil water separators
Relative Size Potential Preferential Pathways	Variable General utilities, pipeline corridors, karst/fractured bedrock (location dependent)	Variable Gravel bed fill, shallow coarser- grained soil, karst/fractured bedrock (location dependent)	Large (many acres/hectares), although smaller parts may be carved out for redevelopment Natural oil seeps, incorrectly abandoned wells, fault structures along which VFCs could migrate, karst or fractured bedrock (location dependent)
Key Assessment Factors	Documenting historical and current uses of the site	Knowing precisely where the pipeline corridor is	Documenting historical and current location of all exploration wells and infrastructure on site and site use

Note: AST = aboveground storage tank; BTEX = benzene, toluene, ethylbenzene, and xylenes; UST = underground storage tank; VFC = vapor-forming chemical.

Table D-3. Selected common petroleum site types.

Characteristic	Former Manufactured Gas Plants	Creosote (Wood-Treating) Facilities	Dry Cleaners Using Petroleum Solvents
Common Indicator Compounds	BTEX, indane, indene, naphthalene, trimethylbenzenes	Naphthalene, alkyl-naphthalene derivatives, benzene	BTEX
Carbon-Chain Range(s) Potential Release Sources	C6–C10 aromatics C10–C36 polyaromatics Tar holders, oil/water separators, gas holder foundations, purifying boxes, tar wells	C6–26 Drip pads, product storage areas, unlined pits, lagoons	C7–C12, C11–C13 Outside building (especially windows and doors), storage areas, dry wells, drains
Relative Size Potential Preferential Pathways	Usually small (minimum 0.2 acres / 0.08 hectares, median 2 acres / 0.8 hectares, average 6 acres / 2.4 hectares); however, some can be larger (maximum 75 acres / 30 hectares) Permeable zones such as gravel layers, storm and sanitary sewers leading off-site, karst/fractured bedrock (location dependent)	Medium to large General utilities, karst/- fractured bedrock (location dependent)	Small; commonly located in strip malls, but can be stand-alone buildings of less than 0.5 acres (0.2 hectares) **Subsurface:** utility corridors, improperly abandoned monitoring wells and karst/fractured-bedrock features **Building structure:** cracks in floors/walls, utility conduit entrances, floor drains and associated piping, karst/fractured bedrock (location dependent)
Key Assessment Factors	Documenting historical and current uses of the site; source areas include gasholders, retort houses, tar wells, oil/water separators, purifying boxes	Documenting historical and current uses of the site; location of pits	Documenting historical and current uses of the site. Past solvent use

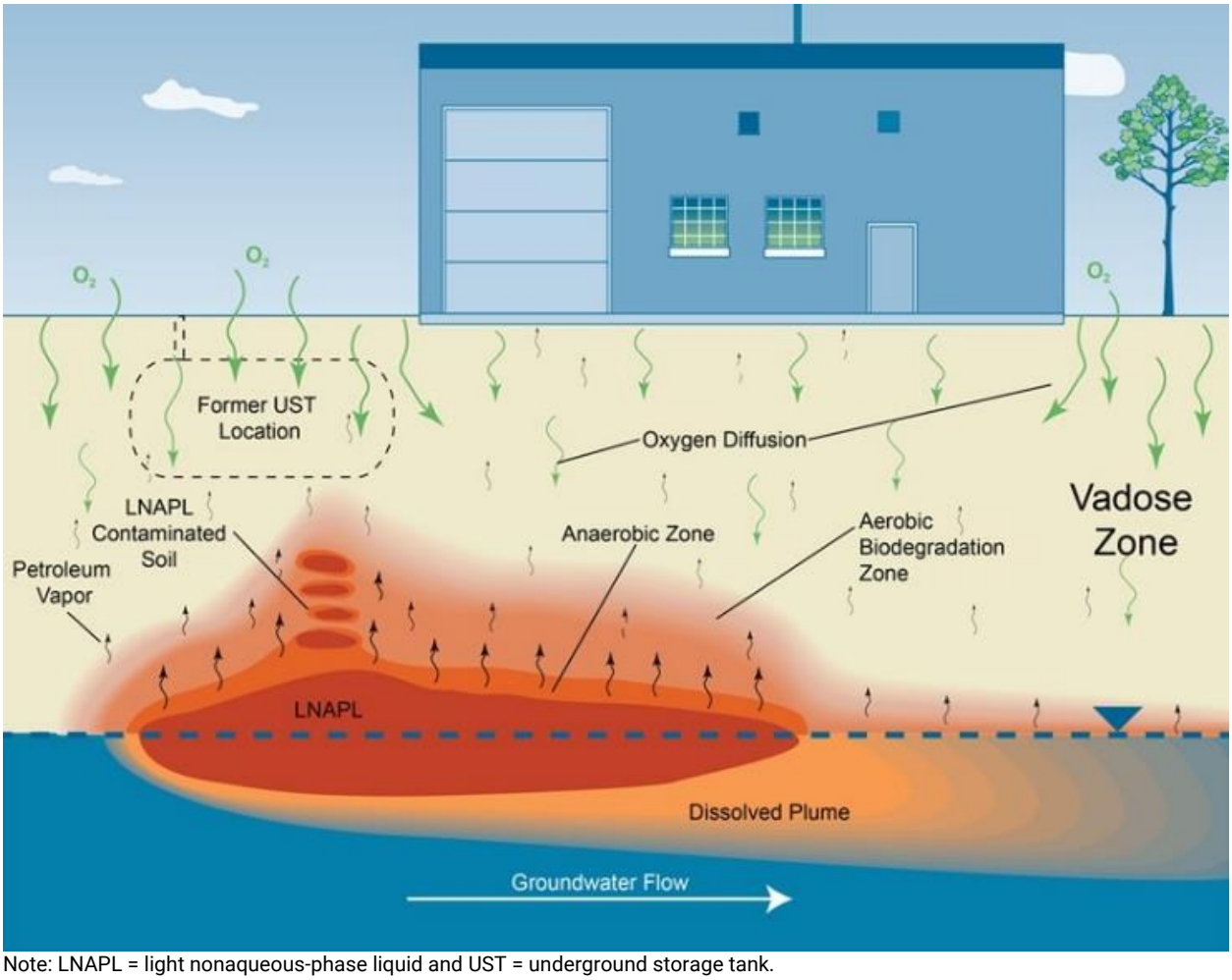
Note: BTEX = benzene, toluene, ethylbenzene, and xylenes.

D.1 Gasoline Underground Storage Tanks and Diesel Underground Storage Tanks

At small-scale facilities, such as gasoline stations, petroleum products are typically stored in USTs. According to information obtained from the U.S. Environmental Protection Agency (USEPA) Office of Underground Storage Tanks, approximately 542,000 USTs nationwide store petroleum or hazardous substances.

Benzene, toluene, ethylbenzene, and xylenes (collectively known as BTEX) and naphthalene are the main indicator compounds that may be of concern for PVI from a petroleum UST release. Methyl tertiary-butyl ether, ethanol and other alcohols, fuel oxygenates, and to a lesser extent certain polycyclic aromatic hydrocarbons (PAHs) are also components associated with releases at USTs. The alcohols and some oxygenates (such as tert-butyl alcohol, an oxygenate [TBA] and n-butanol), however, typically have high aqueous solubilities and low Henry's Law coefficients, which greatly reduce their potential for PVI.

Potential receptors at this type of site may include those present at the filling station, as well as surrounding residential, commercial, and industrial properties. Potential redevelopment of a site for a different use may change the receptors and should be evaluated.



Note: LNAPL = light nonaqueous-phase liquid and UST = underground storage tank.

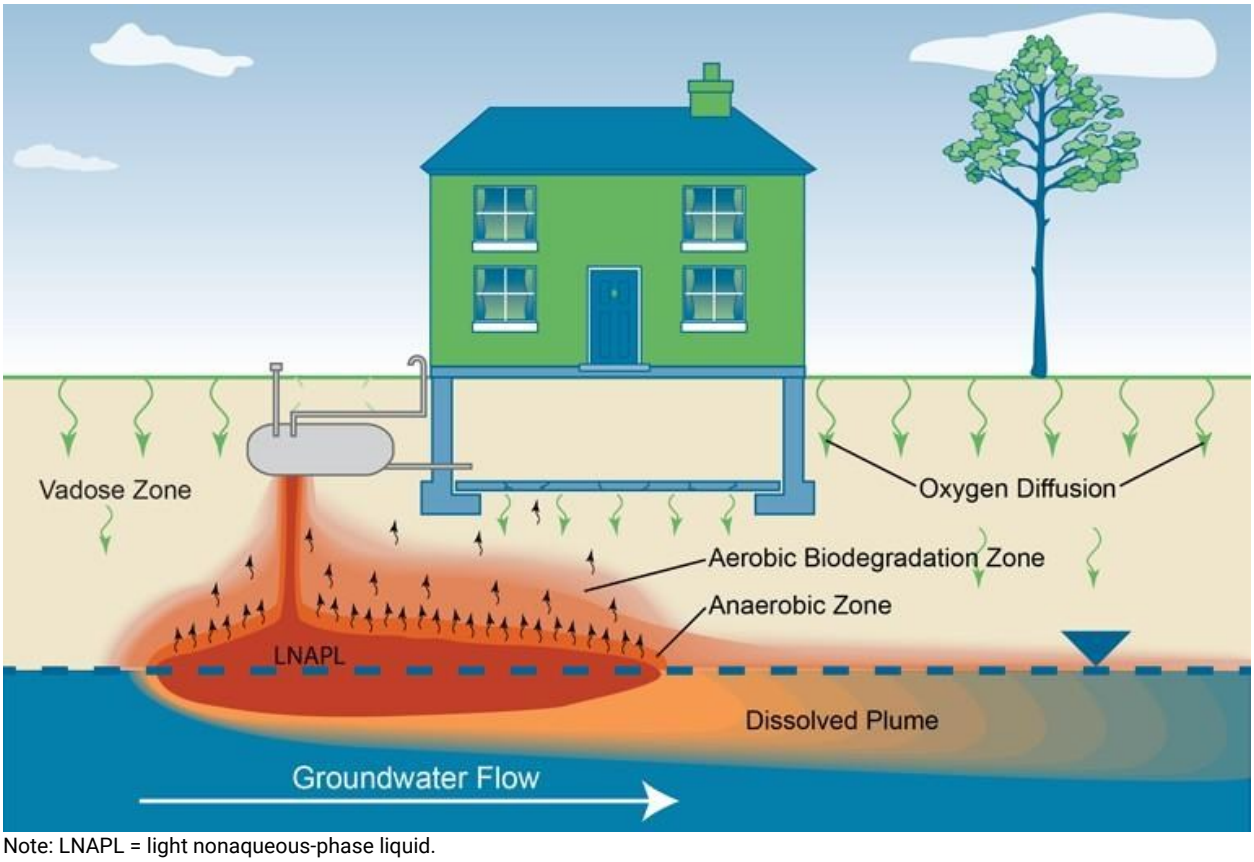
Figure D-1. Petroleum release at a gasoline or diesel underground storage tank site.

USTs may be constructed of steel, which can corrode over time and allow the contents of the tank to leak into the environment. UST releases may happen suddenly (such as a UST/piping rupture) or gradually (such as a UST/piping perforation caused by corrosion). The size of a UST release depends on the capacity and content of the UST, as well as the rate and duration of the release. Petroleum products released from the UST system enter the subsurface and may migrate down through the vadose zone to the water table. Depending on the size of the release, the product may pool as light nonaqueous-phase liquid (LNAPL) at the water table and may also dissolve into groundwater and migrate off-site as a contaminant plume.

Vapors are released from the free-phase LNAPL and contaminated groundwater. Vapor migration may also occur through natural and artificial pathways present in the subsurface, including UST piping corridors to buildings. Contaminated groundwater may migrate into a basement, basement sump, or foundation drain and release PHC vapors into indoor air. If sources of gasoline and diesel vapors are present near a receptor, the potential for PVI is increased. Figure D-1 depicts a typical site with a UST release as it pertains to the potential for PVI.

Additional resources for the evaluation of releases from USTs include guidance documents from the Indiana Department of Environmental Management (IDEM) (2022).

D.2 Commercial/Home Heating Oil Tanks



Note: LNAPL = light nonaqueous-phase liquid.

Figure D-2. Release from a home heating oil tank.

Heating oil is commonly used to heat residential and commercial buildings in many parts of the United States. Releases from commercial and home heating oil tanks are typically small but may range in size

from less than 1 acre (approximately 0.4 hectares) to several acres (hectares) of land. A release from a site that currently uses heating oil will most likely contain No. 2 fuel oil.

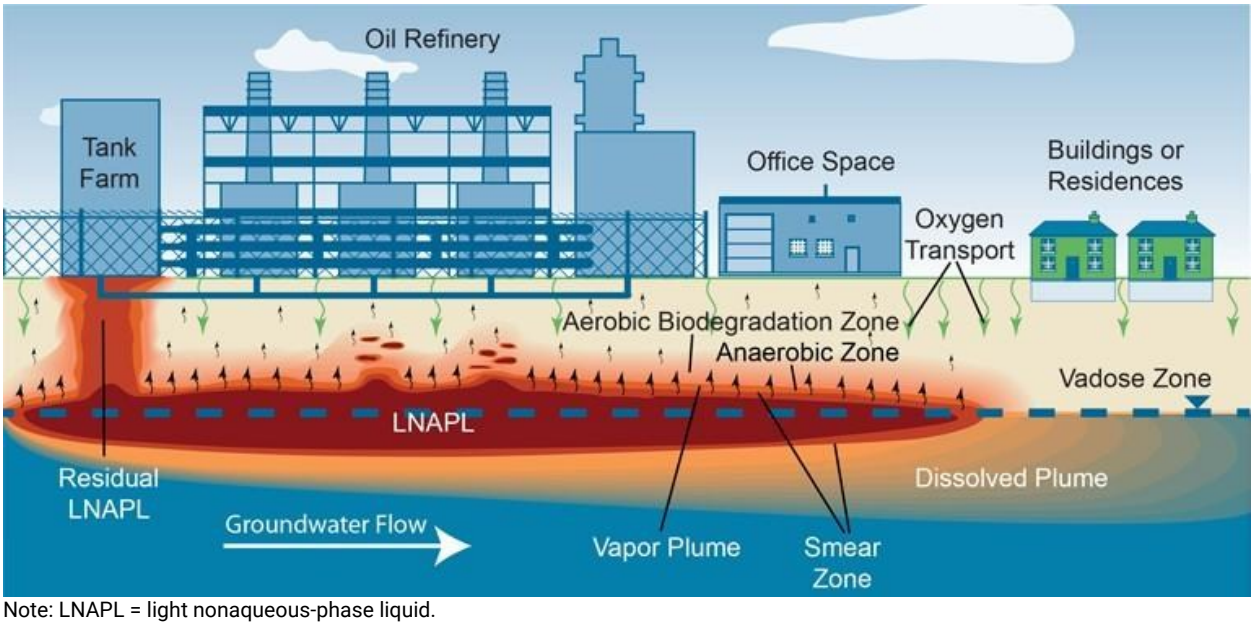
Sites where a historical release is suspected, however, will likely contain No.6 fuel oil, which is a heavier fuel oil.

Heating oil can be stored in either aboveground storage tanks (ASTs) or USTs located inside or outside of the building. The capacity of these tanks can typically range from 250 gallons (946 liters) to 2,500 gallons (9,463 liters), although some tanks may be larger. Releases may be caused by tank corrosion, filter breakage, leakage from the copper line between the tank and furnace, and tank overfills.

Releases from ASTs located on concrete floors in building basements may be more contained within the basement and present a lower potential for PVI (although the release may migrate through the concrete and affect soil and groundwater, which may lead to the potential for PVI). Note that releases from ASTs that are completely contained within the basement may present an indoor air quality issue and are not covered as part of this guidance. Releases from interior ASTs located on dirt floor basements or basement floors with cracks, as well as releases from exterior ASTs located close to the building, may contaminate the groundwater and soil beneath the building, leading to the potential for PVI.

Releases from exterior USTs can have potential for PVI if the UST is located near the building or if the volume of the release is enough to contaminate shallow groundwater beneath the building (see Figure D-2). Vapors originating from a leaking heating oil UST or AST may also enter the building through preferential pathways such as utility conduits, sumps, and drains. BTEX, and to a lesser extent certain PAHs (such as naphthalene), are the primary COCs for PVI from commercial/home heating oil releases. Receptors at residential or commercial fuel oil sites typically include residents of the building and workers in commercial or office settings. Potential redevelopment of a site for a different use may change the receptors and may need to be evaluated. Nuisance odors may trigger an investigation to determine whether PHC odors are associated with PVI or an indoor air background source (indoor sources of PHCs are not covered as part of this guidance document).

D.3 Refineries



Note: LNAPL = light nonaqueous-phase liquid.

Figure D-3. Release at a refinery.

Refineries receive large quantities of unrefined crude oil, which is processed into petroleum products used for fuel and other petroleum-based commercial products (Figure D-3). Refineries are typically large facilities (many acres/hectares) constructed near surface water bodies or large groundwater reserves for use in the process for cooling water, and in the case of navigable surface water bodies, for ease of delivery of crude oil for processing and for shipment of refined petroleum. No new refineries have been built in the United States since 1976.

Conveyance piping at refineries occurs both above and below ground. When releases occur at a refinery, they are typically associated with transfer of the petroleum through the conveyance piping and result from failure of valves or connections, or from corrosion of the infrastructure piping.

Refineries use various large storage vessels that contain a variety of refined products and can also be sources of a release. Petroleum or petroleum products within refineries include feedstocks, intermediate process streams, and final products from a variety of sources. Major petroleum or petroleum products (API 2002) that may drive potential PVI risk include the following:

- Feedstocks: crude oil, natural gas liquids, recycled oil
- Intermediate streams: atmospheric gas oil (light and heavy), naphtha (light and heavy from various units), vacuum gas oil (light and heavy), gas oil (light and heavy), residuum, and aromatics (BTEX, other aromatics)
- Major products: gasoline, jet fuel/kerosene, diesel oil, fuel oil (several grades), asphalt, lubricants, petrochemicals (such as olefins and aromatics), residuum
- Other process streams: used solvent or lean oil, slop oil

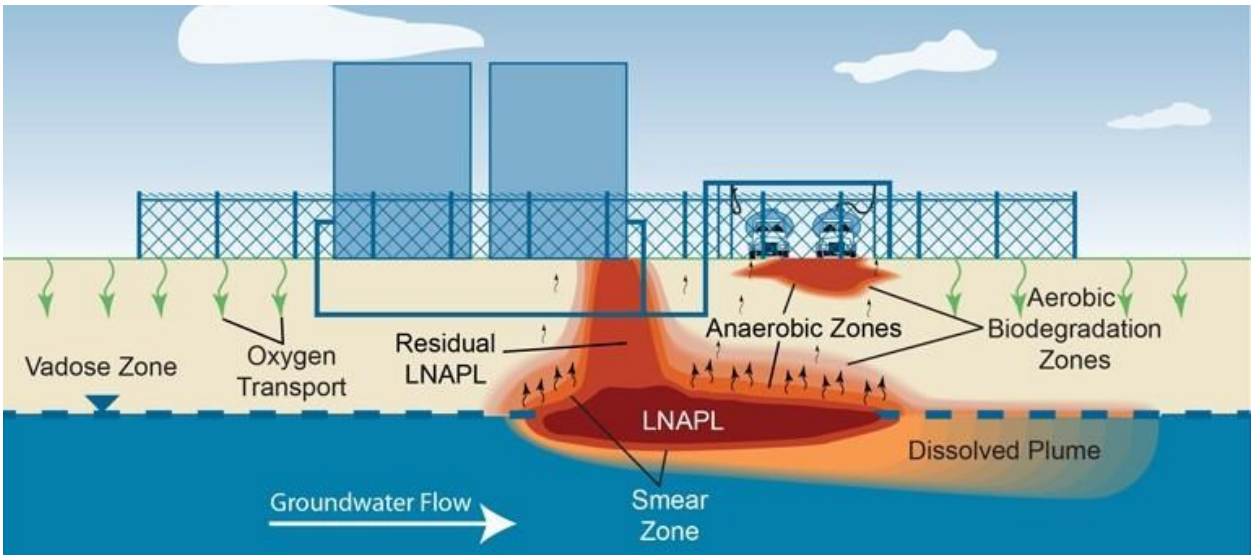
Large volumes of PHCs are transported and managed at refinery sites, so repeated small spills may create incidental areas with LNAPL-contaminated soils. These LNAPL-contaminated soils can be a source for PHC vapors that are unrelated to LNAPL bodies near the water table. Large pools of LNAPL at the water table are also commonly found at these sites and represent a major source for PVI.

Potential risk drivers at refinery sites are highly variable within a refinery and between refineries as a function of the type of feedstock and end products produced at the refinery. Potential redevelopment of a former refinery site for a different use may require PVI assessment.

D.4 Bulk Storage Facilities

A bulk storage facility is one that is used primarily for the storage and transfer of petroleum products. Bulk storage facilities are also referred to as terminals or bulk storage terminals. Bulk storage facilities typically have ASTs with a storage capacity greater than 50,000 barrels (2.2 million gallons / 8.3 million liters) and receive petroleum and refined petroleum products by tanker trucks, barges, rail, or pipelines. The types of refined petroleum products transferred at these types of facilities include gasoline, diesel, jet fuel, and heating oil. This transfer is typically through above or underground piping to delivery trucks or rail cars at the loading racks. Figure D-4 shows typical features at a bulk storage facility.

Petroleum products at bulk storage facilities can be released from surface or subsurface infrastructure. Releases of gasoline (BTEX, naphthalene) present the greatest potential for PVI risk because gasoline contains more volatile components than other petroleum products handled at these sites. Many of the releases are related to the transfer of petroleum from the refinery to the terminal or from the transfer of the stored material to trucks or rail cars. Leaks from the large ASTs are less common than releases associated with the transfer of petroleum products. Typically, releases from storage tanks will be contained within bermed areas, which act as secondary containment; infiltration from spills will vary depending on subsurface geology and whether bermed areas are lined.



Note: LNAPL = light nonaqueous-phase liquid.

Figure D-4. Releases at a bulk storage facility.

The distribution of the released LNAPL depends on the size of the release, location, and the surface and subsurface geology. Surface releases tend to spread following topography. Smaller releases of LNAPL are mainly distributed within the vadose zone; larger releases may migrate to groundwater. Most surface releases are confined to the secondary containment areas at these facilities. Underground releases can migrate to the water table depending upon the amount of product released and the local geology. Guidance and training on the behavior of LNAPL plumes and their relevance to PVI are available from the Interstate Technology & Regulatory Council's (ITRC's) LNAPL guidance (ITRC 2018).

Potential for PVI is minimized when releases are localized and contained within the facility boundaries. The potential for PVI at these sites may be a concern if LNAPL is near an office building or if the property is later redeveloped into another use.

D.5 Pipelines and Transportation

Pipelines constitute a highly specialized transportation system for the movement of crude oil, refined petroleum products, and natural gas. Crude oil, gasoline, jet fuel and many other petroleum products are transported across continents by large distribution networks of underground pipelines (pipelines are usually placed underground to protect them from damage). New pipelines are being built to meet global demand for oil and gas (Hopkin 2007).

Leaks from subsurface pipelines may not be noticed until the product spreads to the surface, so large releases can potentially contaminate deeper soils and groundwater aquifers before the leak is discovered. Pools of dark liquid on the ground surface near the pipeline, discolored or dead vegetation in the area near a pipeline, and PHC odors are some of the indicators of subsurface pipeline leak. Sizes of pipeline spills depend on the length and size of the piping network and duration of the leak or spill. Depending on the size of the pipelines, the volume of product released in a sub-surface spill can be substantial.

Leaks are generally the result of corrosion or cracks in the pipeline; leaks may also occur in the flanges, valves, and other accessories of the pipeline. Knowing the location of the pipeline corridor is a key assessment factor for evaluating pipeline leak sites, and establishing the nature of a release is an important part of the site characterization process. Age of the pipeline, dimensions, history, and products

carried in the line, as well as the history of prior leaks or repairs should also be considered. The typical spill migration path for compounds such as LNAPLs is likely linear (along the length of the pipeline) and downward (under the force of gravity). Depending on the properties of contaminants and the subsurface geology, sufficiently large spills can migrate from vadose-zone soil layers to the groundwater table.

The BTEX compounds in soil and groundwater are the main COCs for pipeline leaks. For VI, benzene is typically the risk driver for petroleum spills from pipelines. Butane, propane, sulfur, methane, and benzene are the main constituents of natural gas pipelines. For natural gas pipeline spills, methane is of greatest concern as a safety issue, and benzene can also be found at elevated levels.

Methane is not a long-term human health-risk driver; however, it is flammable, explosive, and can be an asphyxiant.

Utility corridors for pipelines carrying liquid fuel are typically backfilled with coarse material, such as gravel. These permeable fill materials can act as a preferential pathway, aiding in the movement of vapors laterally and upward to the ground surface. PHCs, however, biodegrade relatively well in vadose-zone soils when O_2 is present. PVI is most commonly associated with free product or high concentrations of dissolved-phase TPH in groundwater near a building foundation (NJDEP 2021). Buildings that are situated very near or over a leaking pipeline should be investigated for PVI if these conditions are identified. Potential redevelopment of a former pipeline corridor for a different use may require PVI assessment. **Figure D-5** illustrates the potential for PVI at pipeline sites.

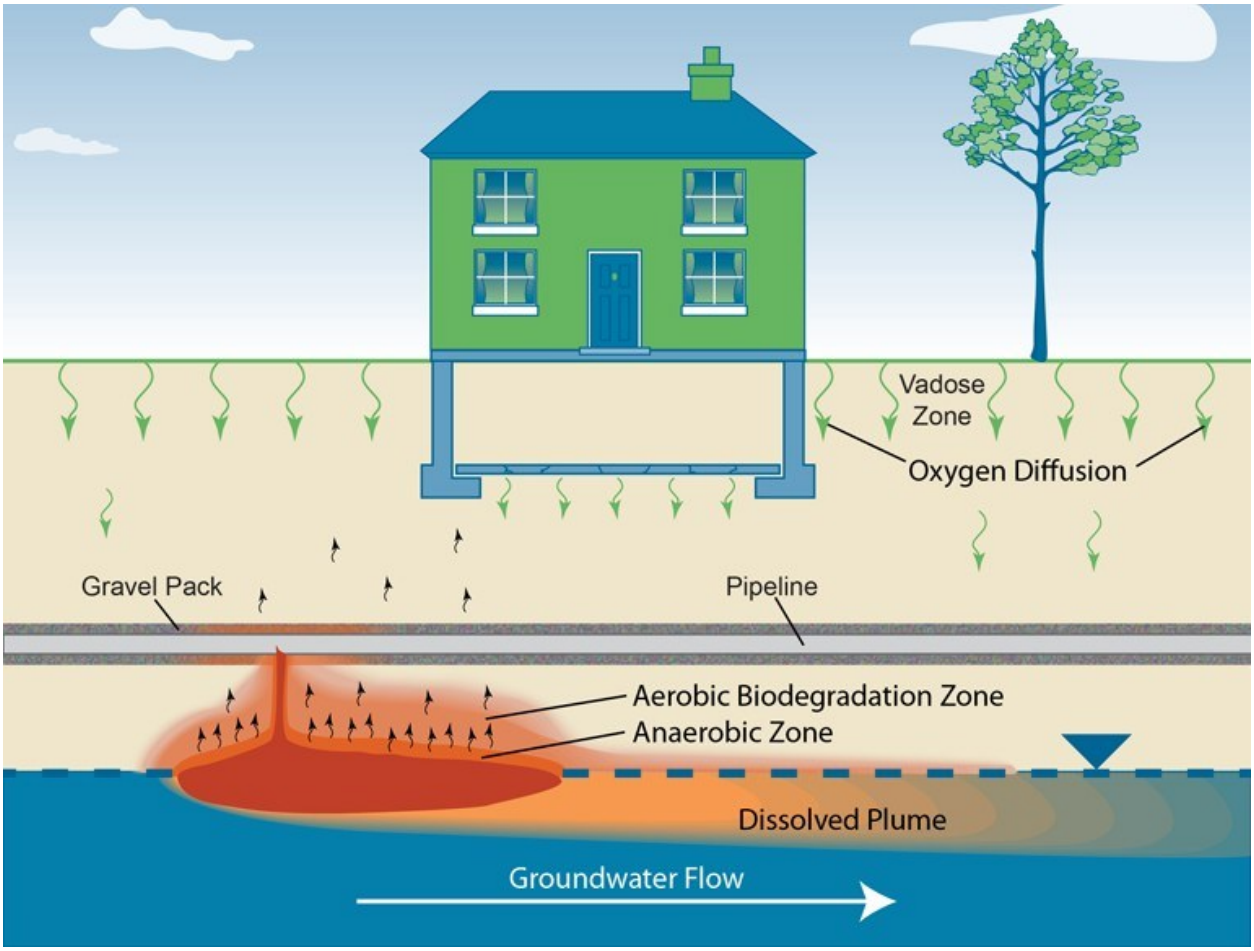


Figure D-5. Release from a pipeline.

D.6 Oil Exploration and Production Sites

Oil exploration in the United States has continued for more than 150 years. Oil exploration began with settlers and Native Americans finding and using natural oil seeps and progressed to the large-scale commercial oil drilling and exploration of today.

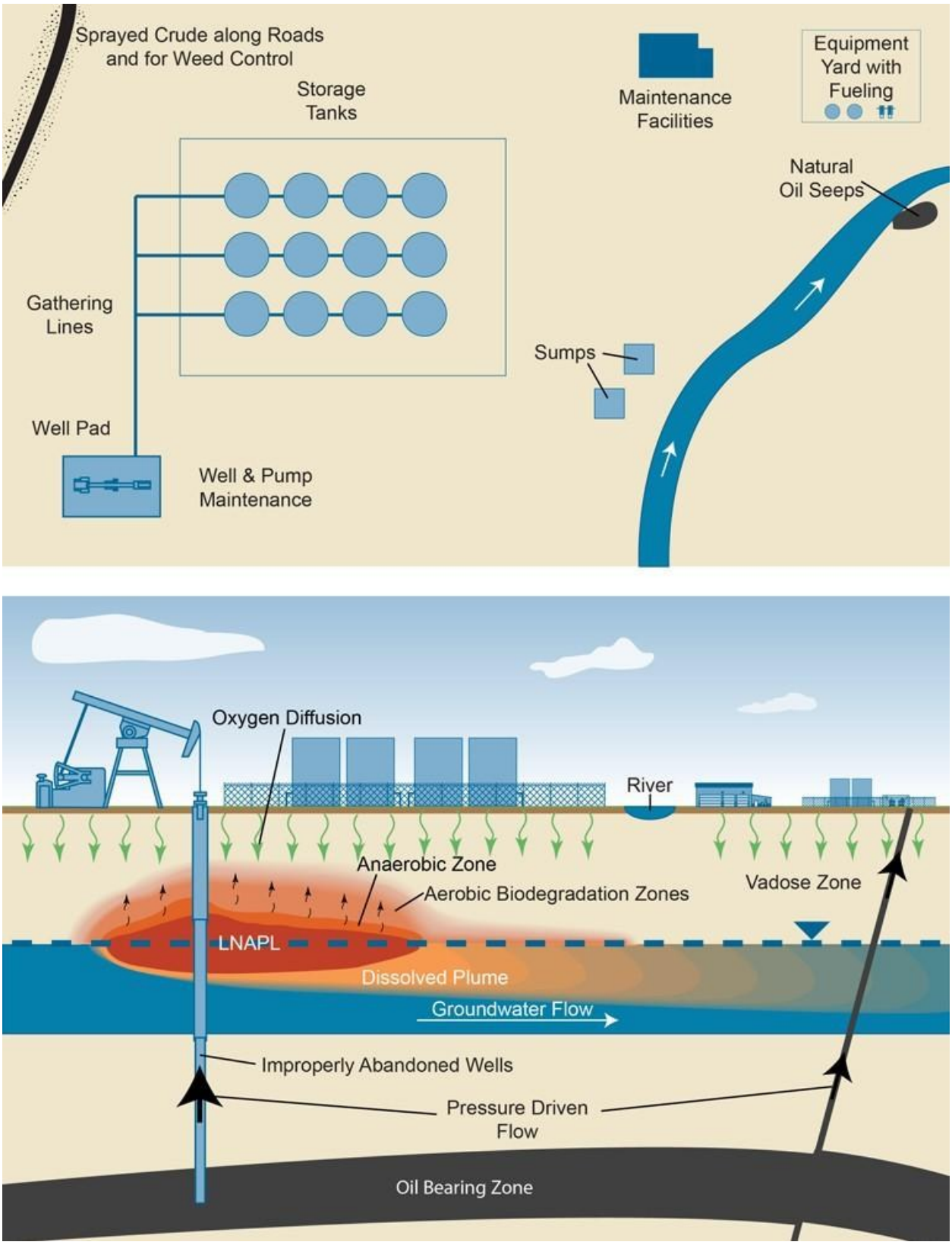
Oil exploration and production (E&P) sites tend to be relatively large and consist of multiple exploration wells as well as staging, collection, and distribution areas. Parts of an E&P site will operate like the bulk storage facility described in **Appendix D, Section D.4**. Petroleum products at E&P sites range from crude oil to a variety of refined products.

The primary risk drivers are BTEX compounds and, at some sites, chlorinated solvents. Methane is also commonly present and is primarily a safety issue. Evaluation of the PVI pathway at E&P sites applies when these sites are either near existing or proposed commercial or residential development or the E&P sites are being considered for redevelopment. **Figure D-6** illustrates potential areas to consider when evaluating the PVI pathway. These areas are located where a preferential pathway may exist or where PHC sources may be concentrated. Areas of greater concern regarding the PVI pathway include natural oil seeps, improperly sealed or abandoned wells, and sumps.

Natural oil seeps are commonly associated with shallow oil fields, especially those in seismically active areas such as California. Many of the older oil fields were discovered because of oil seeps, and natural oil seeps should be evaluated and documented at E&P sites. Seeps follow a pathway from a subsurface oil source to the surface and may contain higher levels of PHC vapors. The presence of seeps should be evaluated by searching available records regarding discovery and exploration at the site and by visual inspection of the site for localized or isolated oil pools. Because natural oil seeps are pressure driven, it is not possible to eliminate this source. It may be possible, however, to control vapors by capture and venting or treatment if necessary.

Pits, sumps, and spills are present at E&P sites and are potential source areas for PVI. Older E&P sites (pre-1990s) may not have lined pits and sumps and thus present the potential for more widespread leakage from these features. These on-site waste and storage facilities can contain a wide range of compounds dominated by PHCs but may include chlorinated compounds as well. A detailed description of the large number of waste materials that can be present in E&P sumps and pits is presented in Wascom's study (2007). Pits, sumps, and spills are easily located through visual inspection of the site. Older or abandoned facilities can be located through evaluation of records of past site use, historical aerial photos, and interviews with former workers. Unlike seeps, sources in sumps and pits can be remediated to reduce or eliminate the potential for PVI.

E&P wells are also present at E&P sites and may provide a potential preferential pathway for the migration of PHC vapors. The potential for PVI by these preferential pathways may be greater in older fields, as shown in **Figure D-6**, where completion methods were not designed to eliminate leakage of reservoir gas to the surface. Many older fields may also contain exploration wells that were abandoned using methods that are not appropriate for eliminating the PVI pathway. Records for the E&P site should be evaluated to locate E&P wells that were drilled on the property. Existing wells should be abandoned properly to reduce potential for future leakage. Older wells may need to be evaluated to determine whether they were abandoned properly. It may be necessary to collect soil vapor samples around older wells to document whether leakage is currently taking place. Gases that are of particular concern at E&P sites include benzene, which is the primary risk driver, and methane, which is the primary safety issue.



Note: LNAPL = light nonaqueous-phase liquid.

Figure D-6. Exploration and production site.

Other features that can be present on E&P sites include tanks, transfer pipelines, well pads, maintenance facilities, equipment yards, and roadways. Records, interviews with past workers, and aerial photos can be used to determine whether these features were present and, if so, where they were located. Existing buildings may need to be removed to reduce or prevent PVI risk. Potential redevelopment of a former E&P site for a different use may require PVI assessment.

D.7 Former Manufactured Gas Plants

A manufactured gas plant (MGP) is an industrial facility where gas was produced from coal, oil, and other feedstocks. MGPs operated from the mid-1800s to around the mid-1900s. The process of gasification generated hydrocarbons that are related to and behave in the same manner as PHC compounds. See **Appendix C** for more information on the chemistry. The gas produced was stored and then piped to the surrounding area, where it was used for lighting, cooking, and heating homes and businesses (NYDEC 2013). MGP sites can range from 0.2 acres (0.08 hectares) to 75 acres (30 hectares) in size, with average and median sizes of 6.1 and 2.0 acres (2.5 and 0.8 hectares) (NYDEC 2013).

During operation of the MGP, a dense, oily liquid known as coal tar would condense at several stages during gas production, purification, and distribution. Although most of the tar was collected for sale or reuse, recovery was usually incomplete. Most plants had tar/water separators, which sometimes could not fully separate the two liquids. The resulting tar/water emulsion was commonly discharged to a nearby surface water body. Over decades of plant operation, substantial amounts of tar also leaked from storage and processing facilities and contaminated surface soils, subsurface soils, and groundwater. Leakage from underground tanks and piping could contaminate soil and groundwater. Historical information including Sanborn Fire Insurance maps, old photographs, and site drawings may be used to identify former buildings and potential source areas.

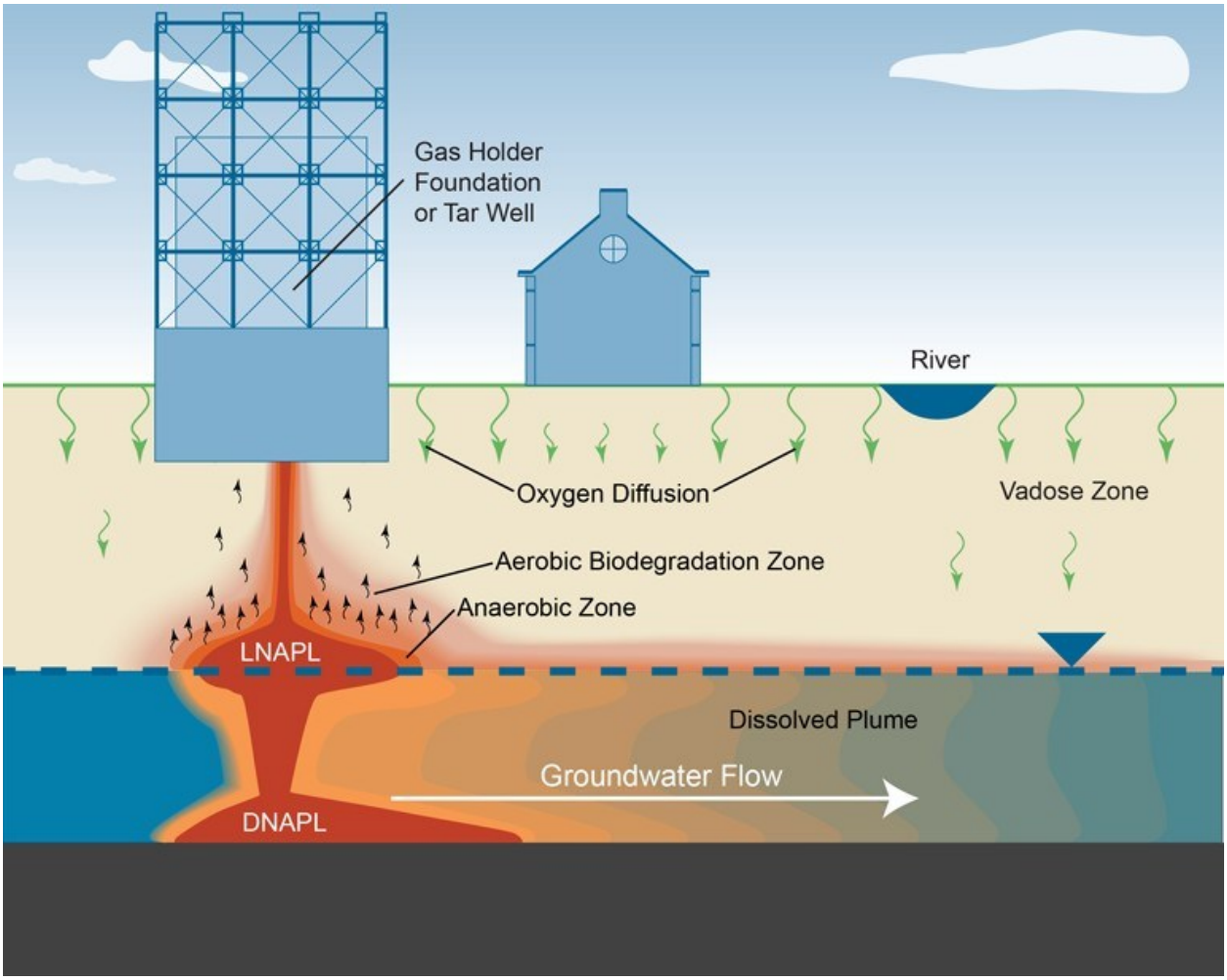
PHCs can generally be found near the gasholders that were used to store gas prior to distribution or near underground tar wells, tar holders, oil/water separators, purifying boxes, or under gas oil storage tanks (kerosene-like oil used in carbureted water gas plants). MGP sites using the coal carbonization process may have separate gas purification areas apart from the retort house.

PHCs present in soil or groundwater generally consist of volatile BTEX compounds and semivolatile PAH compounds. MGP residuals can have a range of densities and may either float on the water table as LNAPL or sink as dense nonaqueous-phase liquid (DNAPL). DNAPLs and LNAPLs may be found above silt layers in the soil or above confining layers such as tills and clays.

PAHs are typically found near site sources because of their affinity to bind to soil and low solubility in water. Aromatic volatile organic compounds may travel farther from sources as dissolved concentrations in the groundwater. Preferential pathways for vapors may include permeable zones such as gravel layers, storm and sanitary sewers leading off-site, and karst/fractured bedrock.

Evaluation of the PVI pathway at former MGP sites begins with identification of potential source areas (**Figure D-7**). Based on the history of MGP sites, potential receptors may include commercial and industrial workers or residents in homes built over or adjacent to the MGP. Although PHCs may be found in the soil or groundwater at MGP sites, there is a growing body of evidence that the potential for PVI is relatively low at most sites. In one study, BTEX compounds were present the subsurface soils at large MGP sites in New York City and Ithaca, New York. Statistically elevated concentrations of these vapor-forming chemicals (VFCs) were not, however, observed in the indoor air (EPRI 2007). The New York State Department of Health also reported preliminary results of an analysis of MGP sites in a VI database. This analysis indicated that levels of MGP-related compounds in indoor and outdoor air at these sites are comparable to concentrations found during background studies (Anders 2012). Another study evaluated data for 10 commercial buildings and 26 single- and multi-family buildings overlying or adjacent to three MGP sites and found no unacceptable inhalation risks due to MGP constituents in indoor air. The authors

suggested that a number of factors may have prevented soil PVI, including a clean layer of ground-ater between the contaminant plume and buildings, as well as natural attenuation through biodegradation of VFCs (DeHate et al. 2011).



Note: DNAPL = dense nonaqueous-phase liquid, LNAPL = light nonaqueous-phase liquid.

Figure D-7. Release at a former manufactured gas plant.

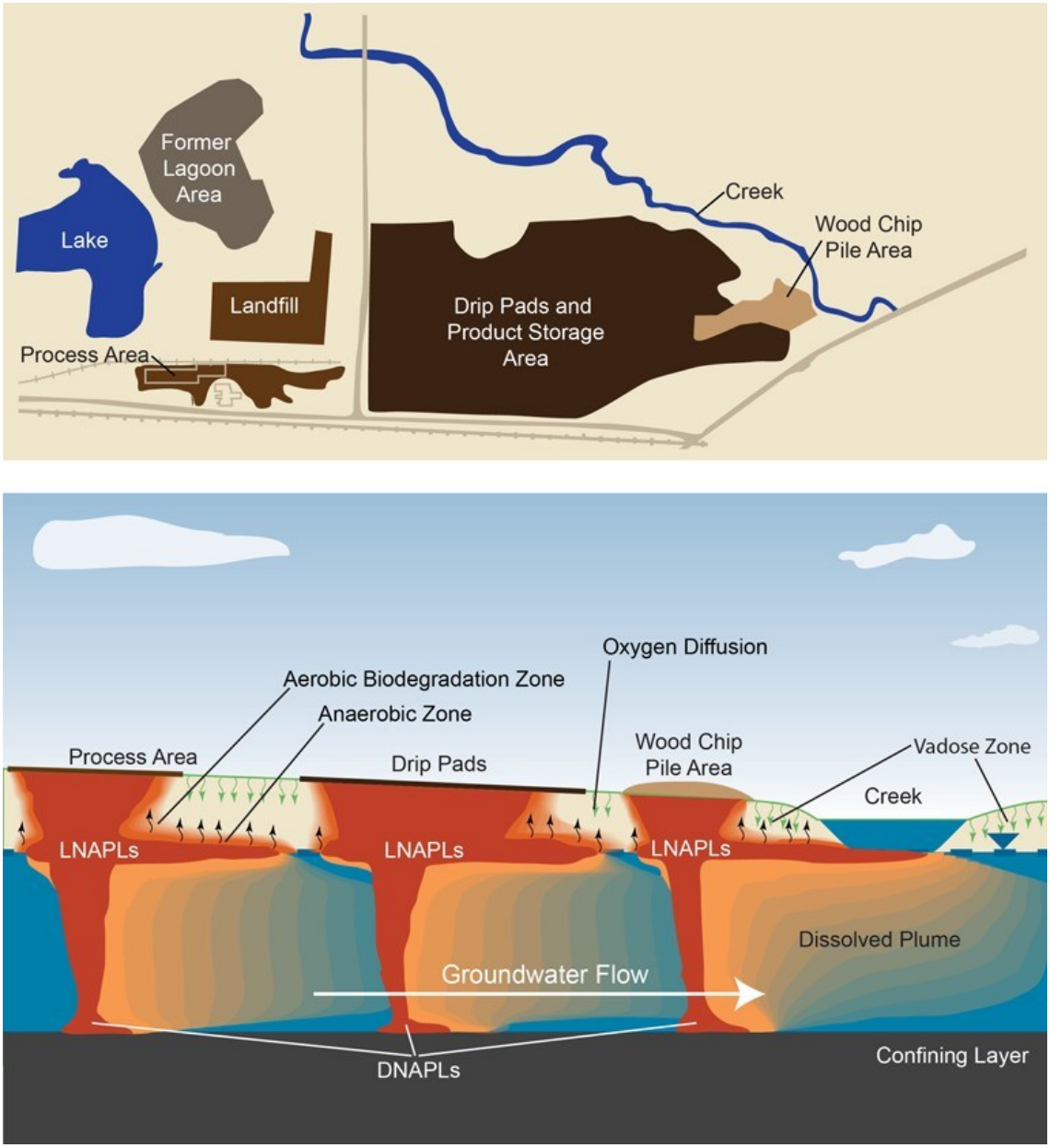
D.8 Creosote (Wood-Treating) Facilities

Creosote (wood-treating) facilities processed coal tar to produce creosote (and other distillation fractions), then treated wood with the creosote. Historically, creosote was refined from coal tar produced at MGPs, but some sources of creosote were refined from pine tar, a by-product of charcoal production. Coal tar creosote was patented in 1836 by Franz Moll, and John Bethell obtained a patent in 1838 for a pressure impregnation process (Freeman et al. 2003). The first factory began treating railroad ties in 1865, and treated railroad ties have since been used across the country. In 2003 alone, U.S. railroad companies installed an estimated 17 million creosote-treated wood ties according to the American Creosote Council website (Creosote Council 2025). Creosote is also used to treat utility poles, marine pilings, and other wood products for outdoor use.

Wood-treating facilities containing creosote and other chemicals have been the subject of numerous Superfund cleanup efforts. USEPA issued a Presumptive Remedy document in 1995 identifying methods to remediate soil and groundwater (USEPA 1995). Areas of potential concern at wood treatment sites

include drip pads, product storage areas, processing areas, unlined pits, unlined surface impoundments, and lagoons. Some wood preserving sites contained both coal tar distillation areas for creosote production and separate wood treatment areas. Creosote sites can range from a few acres/hectares to several hundred acres/hectares with volumes of contaminated soil ranging from tens of thousands of cubic meters to hundreds of thousands of cubic meters. Potential receptors include occupants of buildings built on or adjacent to wood-treating facilities. Potential redevelopment of former wood-treating facilities may require further PVI assessment.

Coal tar creosote is a complex mixture typically composed of approximately 85% PAHs and 2% to 17% phenolic compounds (ATSDR 2024b). The PAHs are generally less volatile and less soluble than VFCs. Coal tars and creosotes are slightly heavier than water and tend to sink when released to groundwater or surface water (**Figure D-8**).



Note: DNAPL = dense nonaqueous-phase liquid, LNAPL = light nonaqueous-phase liquid.

Figure D-8. Release at a creosote (wood-treating) facility.

After reaching the water table, the soluble components may partition to the dissolved phase, and the lighter compounds may volatilize. Therefore, COCs at creosote sites are primarily naphthalene and its alkyl derivatives. BTEX compounds may be present in leachate and contaminated water. As creosote ages, the more volatile and soluble compounds of the mixture diminish relative to the less volatile and soluble compounds (USEPA 2014b). Diesel fuel may also be present since it was often used as a solvent for creosote.

A study of PVI from a soil source has been conducted at the former Reilly Superfund site in St. Louis Park, Minnesota. The results indicate that the risk from VI is within or below the USEPA's acceptable risk range. The five-year review for the Cabot/Koppers site in Gainesville, Florida, suggests that the potential for PVI "…can be evaluated prior to the next Five-Year Review as the protocols are finalized" (USEPA 2011b). Study results of the potential for PVI from a soil source at creosote wood-treating facilities were not available during preparation of this document; however, the potential for PVI may be relatively low because the by-products are similar to those at former MGP sites (Appendix D, Section D.7).

D.9 Dry Cleaners Using Petroleum Solvents

Historically, the most common petroleum product used in the dry-cleaning industry was Stoddard solvent, which is a mixture of aliphatic and alicyclic hydrocarbons in the C7–C12 range. Some currently used high-flash solvents are in the C11–C13 range. Currently, it is estimated that fewer than 15% of dry cleaners in the United States use petroleum solvents.

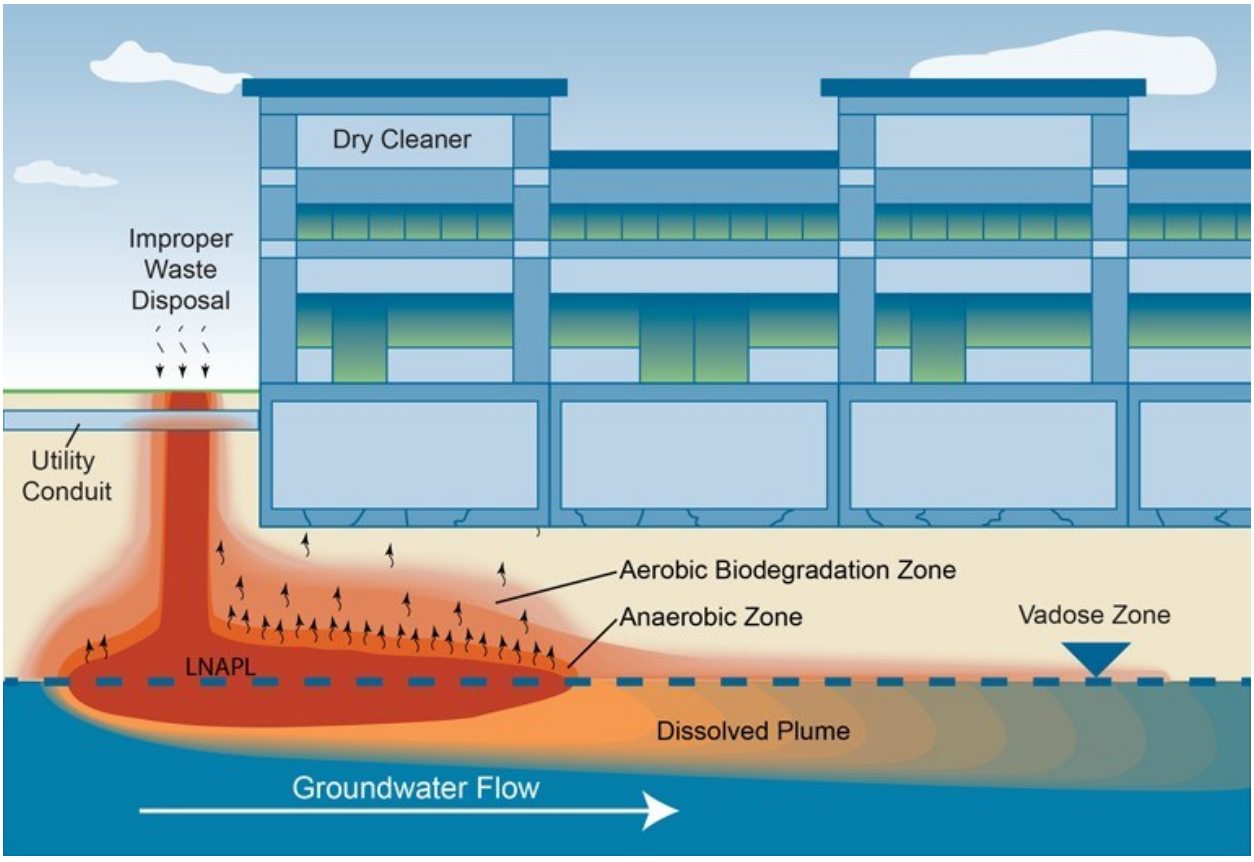


Figure D-9. Release of petroleum-based solvent from a dry cleaner.

Dry-cleaning facilities are commonly located in strip malls but can also be stand-alone buildings on small lots typically less than 0.5 acres (0.2 hectares). Off-site migration of contaminants in groundwater or as

soil vapor plumes poses a potential concern for PVI. Potential receptors may include commercial and industrial workers on-site or residents in homes adjacent to the dry-cleaning facility. Potential redevelopment of a former dry cleaner site for a different use may require PVI assessment (**Figure D-9**).

Preferential pathways for PVI include utility corridors, improperly installed/abandoned/damaged monitoring wells, cracks/holes in floor slabs, basement sumps, and naturally occurring subsurface features such as caves, sinkholes, and fractured bedrock.

Releases to the environment generally occur through improper waste disposal and storage practices. Other sources for a potential release can include spills, container rupture, or faulty equipment. Most spills release less than a few gallons/liters of product; however, poor housekeeping and improper waste disposal practices may release a significantly greater volume of solvent.

Dry-cleaning facilities that use petroleum solvents typically pose a lower risk for VI than facilities that use tetrachloroethene, because petroleum solvents degrade under aerobic conditions. Therefore, an important part of the assessment for the potential for PVI at a dry-cleaning facility is to assess which solvents have been used at the facility throughout the operational history. It is not uncommon for a facility to have switched from one type of solvent to another.

APPENDIX E: APPLICATION OF PRECLUDING FACTORS

A precluding factor assessment is required before implementing distance-based screening (Section 5.3.1). Precluding factors include the following:

- Sources of vapor-forming chemicals (VFCs) in soil or groundwater that are still migrating and could pose a potential vapor intrusion (VI) risk to current and future buildings or occupied buildings located downgradient
- VI preferential pathways (see the Vapor Intrusion Preferential Pathways Fact Sheet) such as conduits for vapor migration (e.g., bedrock, sewer laterals, and utility conduits) that connect the VFC source in soil or groundwater to the building foundation
- Current or future buildings are situated above light nonaqueous-phase liquid (LNAPL) sources with foundations exceeding 66 feet in both length and width based on vapor transport modeling (USEPA 2013a)
- Sources of VFCs are identified within a conduit that directly connects to a building (see the Direct Volatilization to Indoor Air Fact Sheet)
- Vadose-zone soils contain high (e.g., > 4%) fractions of organic carbon (DeVaull 2007) or excessively low moisture content (e.g., < 2% vol/vol) (Holden et al. 1997; Leeson and Hinchee 1996)

If any of these precluding factors are present, then the building cannot be screened out based on source-building separation distance. Proceed to Step 3—Refined VI Screening (see Sections 5.3 and 5.4).

The U.S. Environmental Protection Agency (USEPA) (2015) lists gasoline containing lead scavengers and gasoline containing > 20% vol/vol ethanol as precluding factors. Lead scavengers, 1,2-dichloroethane (also known as ethylene dichloride) and ethylene dibromide (also known as 1,2-dibromoethane), are a VI concern at historical leaded gasoline or aviation gas release sites. Gasoline containing lead scavengers were listed because lead scavengers are halogenated hydrocarbons and are thought to have VI risks that are more akin to chlorinated VFCs, and there was no empirical data available to support the derivation of screening distances at the time of guidance publication. Gasoline containing lead scavengers is now being eliminated as a precluding factor given that the vertical screening distances recommended by the USEPA Office of Underground Storage Tanks (OUST) (2015) have been shown to be broadly applicable for lead scavengers (Hers et al. 2022; Kolhatkar et al. 2019; 2021; Ma et al. 2016). Gasoline containing >20% vol/vol ethanol (e.g., E-85) was also listed by USEPA OUST (2015) as a precluding factor because of the potential for the ethanol to biodegrade anaerobically in groundwater and generate significant amounts of methane gas (a process called methanogenesis), which would then be readily oxidized in the vadose zone and reduce the amount of oxygen (O_2) available for aerobic biodegradation of petroleum hydrocarbons. Studies have shown, however, the highest rates of methanogenesis are typically associated with ethanol fuels containing 10% vol/vol ethanol as compared to those containing > 10% vol/vol ethanol (e.g., E20, E30, E85 and E95) (Chen et al. 2008; Devries 2017; Jourabchi et al. 2012; Nelson et al. 2010). Both lead scavengers and higher ethanol content fuels were considered by the Interstate Technology & Regulatory Council and USEPA as precluding factors in prior guidance documents; hence, it is important to discuss with the applicable regulatory agency the potential elimination of these two factors prior to performing distance-based screening.

Modeling (USEPA 2013a) was used as the primary basis for USEPA OUST (2015) to include building (foundation) size as a precluding factor for petroleum vapor intrusion (PVI) screening at certain sites with LNAPL sources. Aerobic biodegradation was conservatively modeled, assuming no O_2 diffusion through the building foundation. O_2 diffusion through concrete is a relatively common occurrence that affects

concrete durability (Kobayashi and Shuttoh 1991; Tittarelli 2009). In addition, even slight amounts of O_2 diffusion through a building foundation are likely to eliminate the potential for O_2 shadows to develop below building foundations (USEPA OUST 2015; Verginelli, Yao, Wang, et al. 2016).

Soils with excessively high organic content (e.g., certain peats, bay muds, and wetland and deltaic soils with > 4% organic carbon content) are flagged as precluding factors by USEPA OUST (2015) because of the potential to respire naturally and consume significant amounts of O_2 that might otherwise be available for the aerobic biodegradation of petroleum VFCs. USEPA OUST (2015) also precludes distance-based screening at sites with low moisture content soil (e.g., containing < 2% vol/vol) in the vadose zone. These soils are unable to support plant life and have insufficient moisture to support biodegradation. Soils with excessively high organic matter or low moisture content are assumed to be atypical conditions at most PVI sites as inferred by their lack of occurrence at hundreds of petroleum release sites contained in USEPA's PVI database (USEPA 2013c).

This portion of the page left blank intentionally. The next appendix begins on the following page.

APPENDIX F: DISTANCE-BASED SCREENING AT PETROLEUM VAPOR INTRUSION SITES

Information on the vapor-forming chemical (VFC) source type (whether light nonaqueous-phase liquid [LNAPL] or groundwater/dissolved phase) and its extent within the subsurface is essential for applying distance-based screening at petroleum vapor intrusion (PVI) sites. This information is critical for determining which vertical screening distance to apply. There is a higher probability of encountering LNAPL in the vadose zone near or below former or current underground storage tank (UST)/ aboveground storage tank (AST) equipment, in known or suspected release areas, along perching units or low-permeability soil layers, or in a smear zone near the water table. The smear zone may extend well above the water table at some sites with large fluctuations in the water table (e.g., several feet or meters) and may reach beyond locations where mobile LNAPL is detected in monitoring wells. The edge of the VFC source in soil or groundwater can be defined based on applicable state or local regulatory requirements (e.g., maximum contaminant levels, detection levels, or vapor intrusion [VI] screening levels [VISLs]).

Identification of the VFC source type can be particularly challenging at sites where LNAPL is present in the subsurface as a residual phase but is not detectable in groundwater monitoring wells. Table F-1 provides a list of general indicators of residual LNAPL, which can serve as multiple lines of evidence (MLEs) and not applied explicitly as absolute values.

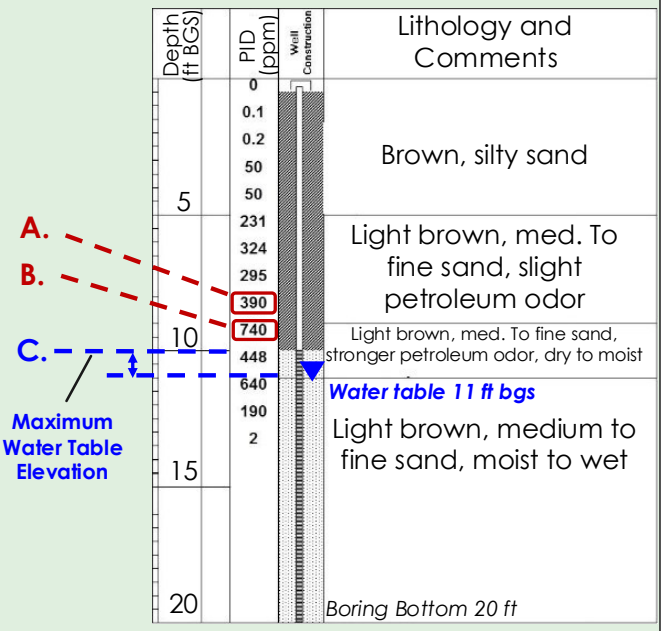
Table F-1. General indicators of residual light nonaqueous-phase liquid (required for distance-based screening at petroleum vapor intrusion sites).

Indicator[1]	Comments
Groundwater	
• Benzene: > 1–5 mg/L[2,3] • TPH Gasoline > 30 mg/L[4] • Benzene, Toluene, Ethylbenzene, and Xylenes (sum of BTEX) > 20 mg/L[5] • Current or Historical Presence of LNAPL (including sheens)[2,3]	There is not a specific petroleum hydrocarbon concentration in groundwater that defines LNAPL because of varying product types and degrees of weathering.
Soil	
• Current or Historical Presence of LNAPL (including sheens, staining)[2,3] • Benzene Concentrations > 10 mg/kg[2] • TPH Gasoline Concentrations > 250[2]–500[5] mg/kg • UV Fluorescence or Laser-Induced Fluorescence Response in LNAPL Range[6] • PID or FID Readings > 500 ppm[7]	The use of TPH soil concentration data as LNAPL indicators should be exercised with caution given that (a) TPH soil concentrations can be affected by the presence of natural organic matter and (b) TPH concentrations in soil are not well correlated with TPH or O_2 concentrations in soil vapor (Lahvis et al. 2013).
Location Relative to Underground Storage Tank / Aboveground Storage Tank	
Adjacent (e.g., within 20 feet of) of a Known or Suspected LNAPL Release Area or Petroleum Equipment[2]	The probability of encountering LNAPL increases closer to a known or suspected release.

Notes: BTEX = benzene, toluene, ethylbenzene, and xylenes; FID = flame ionization detector; LNAPL = light nonaqueous-phase liquid; PID = photoionization detector; TPH = total petroleum hydrocarbons.
1 One or more of these indicators may be used to define LNAPL.
2 Value used in the derivation of screening distances by USEPA (2013c) and Lahvis et al. (2013).
3 Value used in the derivation of screening distances by Peargin and Kolhatkar (2011).
4 Value used in the derivation of screening distances by USEPA (2013c).
5 Value recommended by Lahvis et al. (2013).
6 Value is from ASTM E2531-06.
7 Value recommended by USEPA (2013c) and Lahvis et al. (2013).

Ways to Delineate the Top of an LNAPL Source at PVI Sites

The vertical extent of a petroleum vapor source in soil or groundwater can be estimated to within a foot or two (or < 1 m). As noted previously, USEPA (2015) recommends identifying where residual-phase LNAPL is present based on invoking MLEs and the LNAPL indicator criteria (see **Table F-1**). Photoionization detector (PID) readings > 500 ppm are one such criterion. If PID readings are reported in boring logs, then one could assume the top of a residual LNAPL source is either (A) the base of clean soil where PID concentrations are below 500 ppm, (B) the first encountered LNAPL where PID readings exceed 500 ppm, or (C) the top of the maximum anticipated or reported water-table elevation. Estimating the current or future top of the maximum anticipated water-table elevation may require some professional judgment, such as adding a few feet (or 0.5 m) to account for uncertainty if limited site data are available or the water table was receding during a dry period with little precipitation.



The same residual LNAPL indicator criteria can also be used to define the lateral extent of an LNAPL source in soil or groundwater.

The edge of a LNAPL source is typically defined by the presence of residual phase in soils and groundwater. LNAPL sources can be difficult to identify but are often found in the vadose zone near or below former or current UST/AST equipment, in known or suspected release areas, along perching units or low-permeability soil layers, or in a smear zone near the water table. The LNAPL smear zone may extend well above the water table at sites with large water-table fluctuations. Identification of the VFC source type can be particularly challenging at sites where LNAPL is present in the subsurface as a residual phase but is not detectable in groundwater monitoring wells. General LNAPL indicators are presented in **Table F-1**. These criteria should be used as general guidance or collectively as MLE (see the **Multiple Lines of Evidence Fact Sheet**) recognizing that petroleum VFC concentrations in soil or groundwater can vary significantly depending on the type of LNAPL (e.g., gasoline, diesel, jet fuel) and its residence time in the subsurface (i.e., degree of weathering). In addition, certain regulatory agencies may have their own criteria for identifying residual LNAPL. Identifying residual LNAPL is crucial at this stage to avoid the misapplication of dissolved-phase screening distances to LNAPL sources.

Lastly, as noted in **Section 5.4.1 Concentration-Based Screening**, using VISLs is not recommended at PVI sites, except for sub-slab soil vapor. This cautionary statement stems from the fact that VISLs do not factor in biodegradation in the vadose zone, which results in depth-dependent attenuation factors that vary as a function of source-building separation distance and biodegradation rate. The VISLs are therefore often overly conservative for application to soil vapor screening at PVI sites. The depth-dependence is also not conducive to the application of a bioattenuation factor or multiplier of the VISL to account for biodegradation, unless using it to define a VISL at a specified depth (e.g., California Water Boards 2025).

APPENDIX G: OVERVIEW OF VAPOR INTRUSION MODELS

This appendix provides an overview of vapor intrusion (VI) models. Models for evaluation of VI may be categorized as follows:

- Empirical models, or predictions based on observations from other sites (such as attenuation factors [AFs])
- Analytical models, which are mathematical equations based on a simplification of site conditions (such as the Johnson and Ettinger [J&E] model)
- Numerical models, which allow for simulation of multidimensional transport and provide for more realistic representation of site conditions.

Detailed reviews of analytical and numerical models used in prediction of VI for a range of contaminant types and site condition scenarios are provided in Lahvis (2011), Yao et al. (2013), and Verginelli and Yao (2021).

G.1 Empirical Models

Empirical models are based on observed data for vapor AFs (indoor air concentration divided by subsurface soil vapor concentration) or vadose-zone attenuation distances. There are several approaches for inclusion of aerobic biodegradation of petroleum hydrocarbons (PHCs) in such a framework, including vertical screening distances and bio-reduction factors (for example, 10× or 100×) applied to vapor AFs. These approaches are extensively covered in **Chapter 5: Site Screening**.

Recent advancements in empirical modeling include work by Kram and Solgi (2025) using machine learning to develop building-specific correlations between barometric pressure patterns and exposure concentration measurements during upward flux conditions. The correlations are used to predict past occupant exposure profiles using historical barometric pressure records.

G.2 Analytical Models

Over the past two decades, analytical models have been developed to predict the transport of vapor-forming chemicals from subsurface sources in soil and groundwater to indoor air, with the primary purpose of supporting risk-based management of contaminated lands (Lahvis 2011). To date, analytical models for soil VI assessment have exclusively consisted of one-dimensional or compartmental models with a uniform planar subsurface source at a specified depth. A primary distinguishing feature of analytical models is whether they incorporate biodegradation. In addition, analytical models vary in how the building foundation is represented (such as slab-on-grade, basement, crawl space, or an earthen floor; see Lahvis 2011). A summary and comparison of the various analytical VI models is provided in **Table G-1**.

Table G-1. Summary of analytical vapor intrusion models.

Model (author)	Model Class	Source Media	Building Foundation	Sensitive Parameters	Model Strengths	Model Limitations
Commercially Available/Public Domain Models						
J&E (1991)	SS	GW, SG	Basement, slab-on-grade	All cases: air change rate, building mixing height; depressurized building: Q_{soil} or Q_{soil}/Q_{build}, except when deep/ low D_{eff} becomes diffusion-controlled scenario; not depressurized (no gradient); diffusive properties of cracks and soil are important	Original model, widely used and accepted as a conservative model for a variety of sites.	One-dimensional, uniform, continuous and nondepleting source, depending on formulation limited number of layers, inherently challenging to simulate building processes and estimate inputs
BioVapor (API 2012a)	SS	GW, SG	Basement, slab-on-grade, earthen floor	Biodegradation rate constant; O_2 boundary condition (e.g., airflow rate) at land surface, soil moisture	O_2-limited biodegradation model, simple simulation of TPH fractions, multiple building foundation boundary condition options (including earthen floor), user-friendly, peer reviewed and USEPA-approved	One-dimensional, single soil layer, constant source concentration, difficulty in simulating depth-dependent soil properties
PVIScreen (Weaver 2013)	SS	GW, SG	Basement, slab-on-grade	Biodegradation	O_2-limited biodegradation, sensitivity evaluation	One-dimensional, single soil layer
RISC5—two biodegradation models included are dominant-layer and O_2-limited models (Spence and Walden 2011b)	SS	GW, S, SG	Basement, slab-on-grade	Biodegradation rate constant; O_2 boundary condition of O_2-limited model (e.g., O_2 transfer or Ko coefficient), soil moisture	User-specified attenuation (and bioattenuation) factors, constant and depleting (finite) source term, coupling of vapor intrusion and groundwater flow models, ability to select different vapor intrusion models	One-dimensional, earthen floor building foundations, TPH simulation, O_2 boundary condition model not well defined, transfer coefficient not well defined
Research and Development Models						
Jeng et al. (1996)	T	GW, S	Earthen floor	Biodegradation rate constant, source-zone mass/source depletion, organic carbon	Time-variable/optional source depletion, can evaluate influence of sorption due to soil organic carbon	One-dimensional, no advective flux, biodegradation only in the aqueous phase regardless of whether there is sufficient O_2, TPH simulation
Modified J&E Model or Dominant-Layer (Johnson et al. 1998)	SS	S, SG	Basement, slab-on-grade	Biodegradation rate constant, dominant-layer thickness	Dominant layer defined from site-specific soil vapor depth profile	Simulates biodegradation regardless of whether there is sufficient O_2, TPH simulation

Model (author)	Model Class	Source Media	Building Foundation	Sensitive Parameters	Model Strengths	Model Limitations
Oxygen-Limited Model (Johnson et al. 2000)	SS	S, SG	Basement, slab-on-grade, earthen floor	Biodegradation rate constant, O_2-transfer coefficient at the upper boundary	Only simulates biodegradation when there is sufficient O_2	Requires specifying an O_2-transfer coefficient that may not be available at many sites and may be difficult to estimate
Behavior Assessment Model (Jury et al. 1983)	T	S	Earthen floor	Biodegradation rate constant, source-zone mass, organic carbon, leaching rate	Time-variable, can evaluate influence of sorption due to soil organic carbon	Simulates biodegradation regardless of whether there is sufficient O_2, does not apply Raoult's law for soil sources (i.e., no limit on soil vapor concentrations when source concentrations exceed soil saturation), TPH simulation
Modified Behavior Assessment Model (Jury et al. 1990)	T	S	Earthen floor	Biodegradation rate constant, source-zone mass, organic carbon, leaching rate	Time-variable; can evaluate influence of sorption due to soil organic carbon	Simulates biodegradation regardless of whether there is sufficient O_2, does not apply Raoult's law for soil sources (i.e., no limit on soil vapor concentrations when source concentrations exceed soil saturation), TPH simulation
Vapor Intrusion Model (Mills et al. 2007)	T	AA, GW, S	Combined basement and crawl space	Biodegradation rate constant, organic carbon, building foundation properties	Time-variable, crawl-space simulation, basement, dwelling space air	One-dimensional, simulates biodegradation regardless of whether there is sufficient O_2, TPH simulation, requires more inputs than steady-state models
Modified Orange County Health Care Agency Model (Ririe et al. 1998)	SS	GW, NAPL	Basement, slab-on-grade, earthen floor	Biodegradation factor	Biodegradation factor determined from site-specific soil vapor depth profile	Simulates biodegradation regardless of whether there is sufficient O_2, TPH simulation, default slab attenuation factor (0.01) assumed
T&R Model (Robinson 2003; Robinson and Turczynowicz 2001, 2005)	T	S	Basement, slab-on-grade, crawl space	Biodegradation rate constant, organic carbon, building foundation properties	Time-variable, incorporates building foundation processes, can be run as 1-D or 3-D	Simulates biodegradation regardless of whether there is sufficient O_2, TPH simulation, requires more inputs than steady-state models
Sanders and Stern Model (Sanders and Stern 1994)	T	S	Earthen floor	Biodegradation rate constant, source-zone mass, organic carbon	Time-variable/optional source depletion, can evaluate influence of sorption due to soil organic carbon	Simulates biodegradation regardless of whether there is sufficient O_2, TPH simulation

Notes: AA = Ambient Air; GW = groundwater; J&E = Johnson and Ettinger; NAPL = nonaqueous-phase liquid; S = soil; SG = soil gas; SS = steady-state compartmental model derived from the Johnson and Ettinger model that incorporates first-order biodecay; T = transient model adapted from Jury model that incorporates diffusion, sorption, first-order biodecay and optional source depletion; T&R = Turczynowicz and Robinson; TPH = total petroleum hydrocarbons; and USEPA = U.S. Environmental Protection Agency.

For purposes of this evaluation, the discussion below categorizes analytical models into four classes depending on their key characteristics: steady-state compartmental models, transient models, combined or specialty models, and simple models that include diffusion, first-order decay, and a slab AF. The focus of this section are models that incorporate aerobic biodegradation, although other types of models are also addressed.

G.2.1 Steady-State 1-D Compartmental Models

The first class of analytical models is steady-state compartmental type models, which are the original J&E model (Johnson and Ettinger 1991), and models derived from the J&E model, including the following:

- Modified J&E model based on the dominant-layer model (Johnson et al. 1998)
- Oxygen-limited model (Johnson et al. 2000)
- RISC5, which contains the modified J&E model based on dominant-layer model and oxygen-limited models (Spence and Walden 2011b)
- BioVapor model (API 2012a; DeVaull 2007)
- PVIScreen model (Weaver 2013)

All the above models incorporate first-order biodecay. The main difference between these models is that the O_2-limited model only includes biodegradation when there is sufficient O_2, whereas the dominant-layer model does not. The BioVapor model also incorporates O_2-limited biodegradation and advancements with respect to boundary conditions for O_2 ingress to the subsurface. Another distinguishing feature of the above models is that a solid foundation (basement or slab-on-grade) is assumed with soil vapor advection limited to penetrations in the foundation such as cracks and construction joints. BioVapor and PVIScreen are commercially available models.

G.2.2 Transient Models

The second class of analytical models is transient models, in which concentrations may vary over time. These models are adapted from the Jury model (Jury et al. 1983), which incorporates diffusion, sorption, first-order biodecay, and optional source depletion, and they are described in modeling studies by Sanders and Stern (1994) and Jeng et al. (1996). These models assume an earthen floor. The advantage of the Jury model and its adaptations is that transient processes and the influence of sorption due to soil organic carbon may be evaluated. A disadvantage is that potential O_2 limitations are not represented.

G.2.3 Combined or Specialty Models

The third class of analytical model, through more complex mathematical solutions, combines various subsurface processes and different building foundations (solid foundation or crawl space), and includes:

- Vapor intrusion model (VIM) (Mills et al. 2007)
- Turczynowicz and Robinson (T&R) model (Turczynowicz and Robinson 2001)
- 2-D analytical piece-wise solution (Yao et al. 2016)
- 2-D analytical model for oxygen prediction (Verginelli, Yao, Wang, et al. 2016)

The VIM and T&R models include the following subsurface processes: diffusion, soil vapor advection (in the soil column, VIM model only), sorption, first-order biodecay and mixing of vapor-phase chemicals

within the crawl space and building air space, and contaminant source depletion. These models have similar advantages and disadvantages relative to the adaptations of the Jury model but have the advantage of including building foundation processes.

The two-dimensional analytical model (Yao et al. 2016) incorporates steady-state diffusion and piece-wise first-order aerobic biodegradation limited by oxygen availability and enable prediction of 2-D concentration distribution and AFs. Verginelli et al. (2016) describe an explicit analytical solution for prediction of oxygen concentrations below a slab, for petroleum vapor intrusion (PVI) scenarios with impervious or pervious building foundations. Critical slab-width-to-source-depth ratios and critical source depths for the presence of a sub-slab *oxygen shadow* (i.e., anoxic zone below the building) are provided as a function of key parameters. Verginelli et al. (2016) describe a companion Excel-based model to the above publication.

Modeling studies that do not necessarily address biodegradation include a study by Yao et al. (2013a) where the effects of slab features and intrusion via cracks were simulated using analytical models. Yao et al. (2013) present a model on estimation of contaminant sub-slab concentrations including lateral source-building separation, which are compared to numerical modeling results and database studies.

G.2.4 Simple Models

The fourth class of analytical models consists of relatively simple models that incorporate diffusion and first-order biodecay (but no O_2 limitations), combined with an empirical slab AF to represent attenuation across the building foundation (such as 0.01). One example of this type of model is the modified Orange County Health Care Agency model (Ririe et al. 1998).

G.3 Numerical Models

Numerical models have been applied for over three decades as tools for gaining a better understanding of the VI pathway. Numerical models allow representations of additional detail, such as heterogeneity, geometric complexity, and temporal variability. Typically, they are applied for research purposes to simulate varying processes for vapor transport and effects of key factors. Numerical modeling studies have had a critical role in helping understand influence of the following factors:

- Contaminant properties, including contaminant attenuation and aerobic biodegradation (e.g., Abreu and Johnson 2006; Lahvis and Baehr 1997; Yao, Shen, Pennel, et al. 2013)
- Variation and complexity in site conditions such as contamination sources and buildings (e.g., Abreu et al. 2009b; 2009a; USEPA 2012a)
- Effect of transient conditions and temporal changes in factors affecting VI (e.g., Shen et al. 2012; Suuberg 2020); Suuberg 2020)

Because of their complexity, numerical models require additional data and effort (and therefore increased cost) relative to analytical models. Thus, for practical applications, the potentially improved accuracy of a numerical model should be weighed against the increased effort and cost. A summary of the historical development of numerical models is provided below.

Lahvis and Baehr (1997) developed a numerical model for the simultaneous transport and reaction of hydrocarbon and O_2 vapors under diffusive-dominated conditions and open surface boundary conditions. Such models do not describe the supply of O_2 from the atmosphere to beneath a building, which usually occurs via a combination of diffusion and advection.

Abreu and Johnson developed a more complex numerical model capable of simulating the simultaneous transport of multiple PHC and O_2, the diffusive and advective resupply of O_2 from the atmosphere to beneath a building, and the rate of VI into the building using user-defined building characteristics (such as basement or slab-on-grade). The model can simulate biodegradation with user-defined kinetics. Simulations with the Abreu and Johnson model were used by the U.S. Environmental Protection Agency (USEPA) to describe and analyze the biodegradation of PHC vapors for varying site conditions (Abreu et al. 2009b; 2009a; USEPA 2012a).

The MIN3P-Dusty model is a multicomponent reactive transport model that has been adapted for simulation of VI (Hers et al. 2014). This model was initially designed to simulate geochemical reactions involving solid mineral, aqueous, and gaseous species; advective-diffusive transport of gases; and advective-dispersive transport of dissolved species (Mayer et al. 2002; Molins and Mayer 2007; Molins et al. 2010). The MIN3P-Dusty model can simulate O_2-limited biodegradation and has potential advantages relative to other models in that mechanisms for soil vapor advection, such as non-equimolar diffusion and biodegradation, are included.

There has been continued research in using numerical models to assess biodegradation processes. For example, Picone et al. (2012) developed a 1-D numerical model to investigate diffusion and aerobic biodegradation in variably saturated soil. Yao et al. (2013) used two different 3-D numerical models to assess the influence of different biodegradation rate models. Yao et al. (2018) conducted 3-D numerical model simulations to examine the role of soil texture in PVI for sources in the vadose zone. The results were compared to analytical calculations and statistical analysis of the USEPA's PVI database. In the anaerobic zone, the normalized soil vapor concentration profiles were observed to be similar and independent of soil type, whereas in the aerobic zone, a more significant attenuation was observed in finer grained soils.

Subsequently, Yao et al. (2019) applied the same 3-D model to investigate the effects of the capillary fringe on petroleum vapor biodegradation and attenuation. Where the nonaqueous-phase liquid (NAPL) source is below the capillary fringe, the effect is to reduce upward diffusion rates of hydrocarbon and increase the thickness of the aerobic zone, resulting in significantly reduced potential for VI. When the NAPL smear zone is above the capillary fringe, there is an increased threat of VI for short vertical source-building separation distances. The modeling was generally consistent with empirical data observations that have led to screening distances recommended in this guidance.

Researchers have also developed useful numerical simulators that enable evaluation of various factors on VI including the influence of the building and environmental factors on transient vapor migration. Early work in this area includes multidimensional numerical codes incorporating computational fluid dynamics developed by Pennell and others (2009). Shen et al. (2012) applied a coupled numerical model for fluid flow and vapor transport to understand the effects of rainfall intensity and duration, wetting fronts, and mixing of infiltrating water with groundwater on vapor transport. Depending on the scenarios modeled, these factors had varying influences on soil vapor concentrations and transport. A follow-up numerical modeling study evaluated the effects of changes of indoor air pressure and air exchange rate in VI scenarios (Shen and Suuberg 2016). Suuberg (2020) describes a demonstration project where a numerical modeling tool, COMSOL, was used to study effect of transients (including building pressure variation, soil moisture variation, adsorption) on VI with specific application to two well-studied field demonstration sites.

APPENDIX H: BIODEGRADATION MODEL (BIOVAPOR) PROCESSES, INPUTS, AND CASE EXAMPLES

This appendix covers four main topics:

- Describes the different compartments for the subsurface to indoor air transport pathway and a coupled model for mass transfer between compartments (excluding biodegradation), which provides valuable insight on the relative attenuation between different compartments.
- Describes biodegradation models and provides a compilation of biodegradation rate constants.
- Discusses how to interpret and use rate constants; these tools and resources are intended to support site-specific modeling applications. This discussion is aligned with conceptual models and parameter definitions as applied in the Johnson and Ettinger model (which neglects biodegradation), the BioVapor model, and the PVIScreen model. Other models (Appendix G) may use similar or closely related parameters.
- Presents case examples of BioVapor model applications.

H.1 Subsurface to Indoor Air Vapor Pathway and Model Compartments

This section presents a description for subsurface to indoor air vapor migration in terms of coupled model compartments; each is described briefly below:

- **Indoor building environment:** This area is the indoor, occupied living space.
- **Building foundation:** This area of the building is in contact with soil and can include basements, slab-on-grade foundations, or crawl-space foundations.
- **Subsurface environment:** This area includes the soil and groundwater below and adjacent to the building, as well as between the building and the subsurface chemical vapor source.
- **Vapor Source:** Vapors may originate from residual light nonaqueous-phase liquid (LNAPL) or from a downgradient groundwater plume resulting from dissolving LNAPL.

Flux between these compartments must be balanced using conservation of mass principles. For example, the indoor air concentration times the air exchange rate in the building rate must equal the rate of mass flux through the floor. If the exchange rate goes up, then the concentration in indoor air will go down.

Biodegradation is a key process that reduces mass flux. Biodegradation can significantly attenuate petroleum hydrocarbon (PHC) concentrations in soils under aerobic soil conditions. O_2 depletion may occur in the subsurface when O_2 demand due to degradation exceeds the available O_2 flux to the subsurface.

H.1.1 Indoor Building Environment

The indoor living space occupied by people is defined most simply by an indoor volume V (m^3) and air exchange rate (ER) (1/day), where ER is the air volume changes in the building per day. Air enters and

leaves the enclosure through windows, doors, walls, ceilings, and floors, and by mechanical ventilation. Air exchange varies over time because of weather, operation of the building (mechanical ventilation systems), and building use patterns. The indoor volume is equivalently defined as equal to the building foundation area, A_f, times an effective mixing height, $L_{mix} = V/A_f$. Chemical mass transfer through the building occurs at a rate proportional to ($ER \times L_{mix}$). More complex representations of the indoor environment can include multiple indoor compartments, including varied floors and rooms of a building, and air exchange across each of the indoor air spaces.

H.1.2 Building Foundation

The building foundation is the area of the building in contact with soil, through which chemicals in the subsurface may migrate to indoor air by either advection or diffusion of soil vapor (or both) through the building foundation. Foundation types include basement, slab-on-grade, and crawl space. Materials of construction for a foundation may vary and can include, for example, bare earth, cobbles, wood, cinder block, and concrete. In addition to materials of construction, air infiltration through a foundation may also be affected by penetrations, such as cracks, underground utilities (water, gas, sewer, and electric), and sumps or drains, through which chemicals may preferentially enter a building. Chemicals can enter either through the conduit itself (a sewer line, for example) or through the backfill soils surrounding the conduit. Chemical mass transfer through a building foundation can be defined in terms of either effective airflow, as Q_f / A_f, or effective diffusion, as D_{eff} / L_f, where Q_f is foundation airflow, D_{eff} is the diffusion coefficient through the foundation, A_f is the area of the foundation, and L_f is the thickness of the foundation.

For convenience, vapor transfer through a building foundation is often described in terms of a foundation airflow Q_f for a specified foundation area, A_f, based on measured chemical concentrations in and below the building. This use of Q_f is convenient but may not represent the underlying physical mechanisms, which may be a combination of both diffusion and advection. An average range of approximately Q_f = 1 to 10 L-air/min for a concrete foundation of area A_f = 100 m^2 in contact with the ground is suggested (Hers et al. 2003).

For an open soil surface, such as a dirt floor or crawl-space foundation, rates of O_2 mass transfer into the subsurface are higher and can be represented in the BioVapor model by specifying a constant O_2 concentration at the soil surface.

H.1.3 Subsurface Environment—Vadose Zone

The subsurface environment includes the soil and groundwater below and adjacent to the building, as well as between the building and the subsurface chemical vapor source. The subsurface environment may include vadose-zone soils, a capillary fringe, and a water-saturated groundwater zone. The capillary fringe interface separates the vadose zone and groundwater. This description is simplified; subsurface stratigraphy can be complex. Chemical vapor mass transfer through a layer of soil where diffusion dominates is proportionate to D_{eff}/L_T, where D_{eff} is the effective diffusion coefficient through the soil layer and L_T is the thickness of the soil layer. In a layered system, overall diffusion can be estimated from sequential diffusion through each of the layers. The overall rate of diffusion in such systems tends to be controlled by the rate of diffusion through the finest-grained layers because of lower air-filled porosity.

Vapor and gas diffusion rates through a porous soil matrix are significantly higher when the air space in the soil matrix is connected. This connection occurs when the air-filled fraction of soil, $\theta_{T\text{-}soil}$ (cm^3-air/cm^3-soil) is greater than approximately 0.2, depending on soil structure. Vapor diffusion is significantly less when the air-filled fraction of soil porosity is disconnected. Disconnection occurs in wetter soils and near the water-table capillary fringe. Soil moisture, $\theta_{w\text{-}soil}$ (cm^3-water/cm^3-soil), which occupies the remaining soil void, can therefore significantly affect diffusion in the soil matrix.

H.1.4 Vapor Source

Persistent sources of subsurface vapors in the subsurface originate from residual LNAPL resulting from a spill or release to the environment. Vapors may either originate directly from LNAPL or from a downgradient groundwater plume resulting from dissolving LNAPL. PHCs are lighter than water, and LNAPL from a release is most often trapped at the water-table interface and within the capillary fringe.

Soil vapor concentrations from dissolved groundwater concentrations are typically estimated by an equilibrium partitioning model and Henry's Law coefficient. Soil vapor concentrations adjacent to LNAPL are estimated with Raoult's law. Partitioning of specific components using Raoult's law is an essential consideration when predicting vapor intrusion (VI) from petroleum LNAPL sources. This consideration is typically unnecessary when predicting VI at sites with releases of single chemicals, such as sites with chlorinated solvent releases. In both cases measured vapor concentrations may be lower than equilibrium estimates because of diffusion-limited mass transfer either through water-saturated soil zones or through bulk LNAPL thickness and biodegradation.

H.2 Comparison of Mass Transfer Rates and Relative Attenuation

Migration rates of vapors through buildings, foundations, and soils may be qualitatively compared using mass transfer parameters. Choosing nominal parameter ranges, the mass transfer rates and relative attenuation are calculated as shown in Table H-1. The relative attenuation is calculated by simultaneously solving an equation for mass transfer rate for each compartment considered.

Table H-1. Comparison of relative attenuation across compartments.

Compartment	Nominal Parameters	Coefficient	Mass Transfer Rate	Relative Contribution to Attenuation*	Relative Contribution to Attenuation†
Indoors	ER = 12/day, L_{mix} = 2.44 m	L_{mix} ER	29 m/day	1.6E-5	0.001
Foundation	Q_f = 5 L/min, A_f = 100 m^2	Q_f/A_f	0.072 m/day	0.007	0.35
Soils—Air Connected	D_{eff} = 0.12 m^2/day, L_T = 3 m	D_{eff} / L_T	0.04 m/day	0.012	0.64
Soils—Wet	D_{eff} = 0.15E-4 m^2/day, L_T = 3 cm	D_{eff} / L_T	0.0005 m/day	0.98	--
			Sum:	1.0	1.0

Note: A_f = foundation area, cm = centimeters, D_{eff} = effective diffusion coefficient, ER = exchange rate, L/min = liters per minute, L_{mix} = mixing zone height, L_T = layer thickness, m = meters, m/day = meters per day, m^2/day = square meters per day, Q_f = soil vapor flux into building.
* Includes the resistance of wet soils in a capillary fringe.
† Neglects the contribution of capillary fringe resistance.

The table illustrates that, when present, diffusive attenuation across a capillary fringe can be substantial. Attenuation across a typical (concrete) foundation is equivalent to that through several meters of soil. Biodegradation is not included in Table H-1 but is discussed in a later section.

H.3 Biodegradation Processes and Rates

Biological degradation of PHC vapors can occur relatively rapidly in aerobic subsurface soils. In aerobic conditions, PHC vapors, in the presence of microbial enzymes, react with O_2 to produce carbon dioxide and water.

$$C_nH_m + \left(n + \frac{m}{4}\right) \cdot O_2 \rightarrow \left(\frac{m}{2}\right) \cdot H_2O + n \cdot CO_2$$

Similar balance equations are applied for alcohols, ethers, and non-hydrocarbons in estimating oxygen demand. The mass ratio of chemical to O_2 consumption for PHCs (neglecting biomass growth), based on the above equation, is approximately 0.3 g-hydrocarbon/g-O_2 for many fuel hydrocarbons. O_2 concentrations in air are approximately 280 g/m^3. O_2 from the soil surface is often a substantial source of O_2 for aerobic degradation of PHC vapors in the subsurface.

Anaerobic degradation with alternate electron acceptors (nitrate, sulfate, iron, etc.) can occur with petroleum but is often neglected in VI estimates as there is not a ready source for replenishment of these electron acceptors. Petroleum can also degrade under fermentative/methanogenic conditions, to produce methane and carbon dioxide.

Petroleum, including both chemicals of direct concern (benzene for example) and other chemicals, biodegrades and consumes O_2 in soils. Aerobic biodegradation depends on the O_2 ingress to the subsurface. Assumptions applied in modeling O_2 limited biodegradation are important as described for the BioVapor model in Section 9.3.3.

H.3.1 Degradation Rate Constants

Modeling requires consistent definition and use of degradation rate constants. Tabulated values without specific definition or developed for other uses (such as groundwater transport or wastewater biotreatment) should not be directly applied in vapor fate and transport modeling. In the BioVapor model, for example, degradation is defined in terms of a first-order water-phase aerobic degradation rate, k_w (1/hr). That is, degradation is presumed to occur only in the water phase of the soil matrix, at a rate proportional to chemical concentration in the water phase, and when O_2 is present.

Different types of rates, including zero-order rates (independent of concentration), instantaneous rates, and rates proportional to soil concentrations (rather than water concentration) have been applied in various soil vapor transport models. More complex forms of rate parameters can also be specified and defined, including Monod-type kinetics (Monod 1949), which is a combination of asymptotic zero and first-order rates; dual-Monod kinetics (Kissel et al. 1984; 1985), which includes both O_2 and hydrocarbon in the rate definition; and formulations that include biomass growth and decay estimates. More comprehensive discussion of these forms of rate parameters are discussed elsewhere (Alexander 1999; Hers et al. 2000). The more complex forms are not necessarily better because there is often a lack of valid and generally available estimates for the needed additional model parameters.

A compilation of first-order water-phase biodegradation rate statistics from laboratory and field studies is shown by DeVaull (2007; 2011), for air-connected vadose-zone soils and is shown in Figure H-1 and Table H-2. Note that the values in Figure H-1 and Table H-2 are based on field data. As part of a sensitivity analysis, a range of rate constants should be simulated. The most likely rates in the distribution are the median (or geometric mean) values in Table H-2 and are a reasonable starting point for modeling. The lowest rates in this empirical data set may have been derived, in some cases, for soils that were not actually uniformly aerobic air-connected soils.

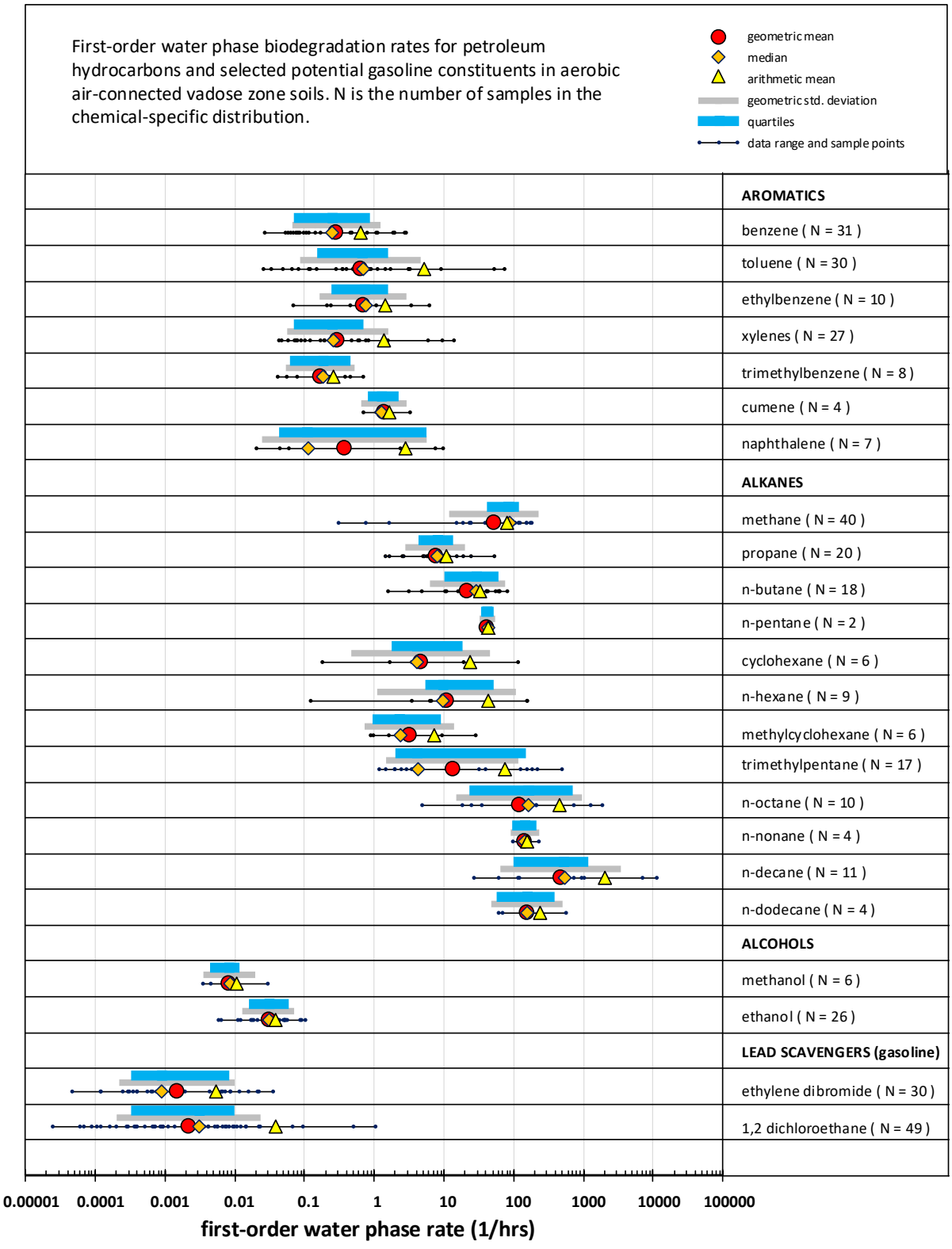


Figure H-1. First-order water-phase biodegradation rates (1/hr) in air-connected aerobic vadose-zone soils.

Source: DeVaull (2011), used with permission.

Table H-2. First-order water-phase biodegradation rates (1/hour) in aerobic vadose-zone soils.

Chemical	Data Count	Media n	Data Range: (1st to 3rd quartiles)	Geometric Mean, mg	Geometric Mean x / , Geometric Standard Deviation (mg/sg to mg · sg)	Geometric Standard Deviation, sg	Arithmetic Mean, ma	Arithmetic Mean Estimated from Lognormal Distribution ma = mg · exp (0.5 · ln(sg)2)	Data Range (minimum to maximum)	95% Bound on Lognormal Distribution Estimate
Aromatics										
Benzene	31	0.27	(0.087–0.78)	0.3	(0.079–1.2)	3.8	0.67	0.75	(0.028–3)	(0.04–2.3)
Toluene	30	0.72	(0.19–1.4)	0.67	(0.1–4.4)	6.6	5.5	4	(0.028–77)	(0.052–8.6)
Ethylbenzene	10	0.79	(0.31–1.4)	0.74	(0.19–2.8)	3.8	1.5	1.8	(0.072–6.6)	(0.098–5.5)
Xylenes	27	0.27	(0.089–0.64)	0.32	(0.067–1.5)	4.7	1.4	1.1	(0.045–14)	(0.034–2.9)
Trimethylbenzene	8	0.2	(0.077–0.42)	0.18	(0.064–0.51)	2.8	0.27	0.31	(0.044–0.73)	(0.033–0.99)
Cumene	4	1.4	(1–2)	1.5	(0.76–2.8)	1.9	1.7	1.8	(0.73–3.4)	(0.39–5.5)
Naphthalene	7	0.12	(0.054–5)	0.38	(0.028–5.2)	13	2.9	11	(0.021–9.8)	(0.015–10)
Aliphatics										
Methane	40	88	(50–100)	53	(13–210)	4	80	140	(0.31–190)	(6.8–410)
Propane	20	6.5	(4.5–9.3)	6.1	(2.5–15)	2.4	8.9	9.1	(1.2–42)	(1.3–29)
N-butane	18	24	(8.7–38)	16	(5.1–49)	3.1	24	30	(1.1–59)	(2.6–96)
N-pentane	2	42	(40–45)	42	(36–49)	1.2	42	42	(37–47)	(18–97)
Cyclohexane	6	4.1	(2.1–16)	4.7	(0.53–42)	8.9	24	51	(0.18–110)	(0.27–82)
N-hexane	9	9.6	(6.3–44)	11	(1.2–96)	8.8	43	120	(0.12–160)	(0.63–190)
Methylcyclohexane	6	2.4	(1.2–8)	3.3	(0.83–13)	4	7.5	8.5	(0.9–29)	(0.43–26)
Trimethylpentane	17	4.2	(2.4–130)	13	(1.7–110)	8	75	110	(1.2–490)	(0.85–210)
N-octane	10	160	(27–580)	120	(17–860)	7.1	440	820	(4.9–1900)	(8.7–1700)
N-nonane	4	140	(110–180)	150	(100–210)	1.5	150	160	(97–230)	(51–410)
N-decane	11	530	(120–980)	470	(73–3000)	6.5	2000	2700	(26–11000)	(37–6000)
N-dodecane	4	160	(67–320)	150	(53–450)	2.9	240	280	(60–570)	(27–890)

Chemical	Data Count	Media n	Data Range: (1st to 3rd quartiles)	Geometric Mean, mg	Geometric Mean x / , Geometric Standard Deviation (mg/sg to mg · sg)	Geometric Standard Deviation, sg	Arithmetic Mean, ma	Arithmetic Mean Estimated from Lognormal Distribution ma = mg · exp (0.5 · ln(sg)2)	Data Range (minimum to maximum)	95% Bound on Lognormal Distribution Estimate
Alcohols										
Methanol	6	0.0081	0.0051–0.0094	0.0080	(0.0042–0.0090)	2.1	0.01		(0.0047–0.021)	
Ethanol	26	0.030	0.018–0.049	0.029	(0.015–0.032)	2.1	0.037		(0.024–0.070)	
Lead Scavengers (Gasoline)										
Ethylene dibromide	30	0.0009	0.00039–0.0071	0.0015	(0.0013–0.0075)	6.0	0.0054		(0.00085–0.034)	
1,2-dichloroethane	49	0.0022	0.00039–0.0083	0.0022	(0.0019–0.018)	9.5	0.039		(0.0031–1.03)	

Note: The values in Table H-2 and Figure H-1 are based on field data.

Source: DeVaull (2011).

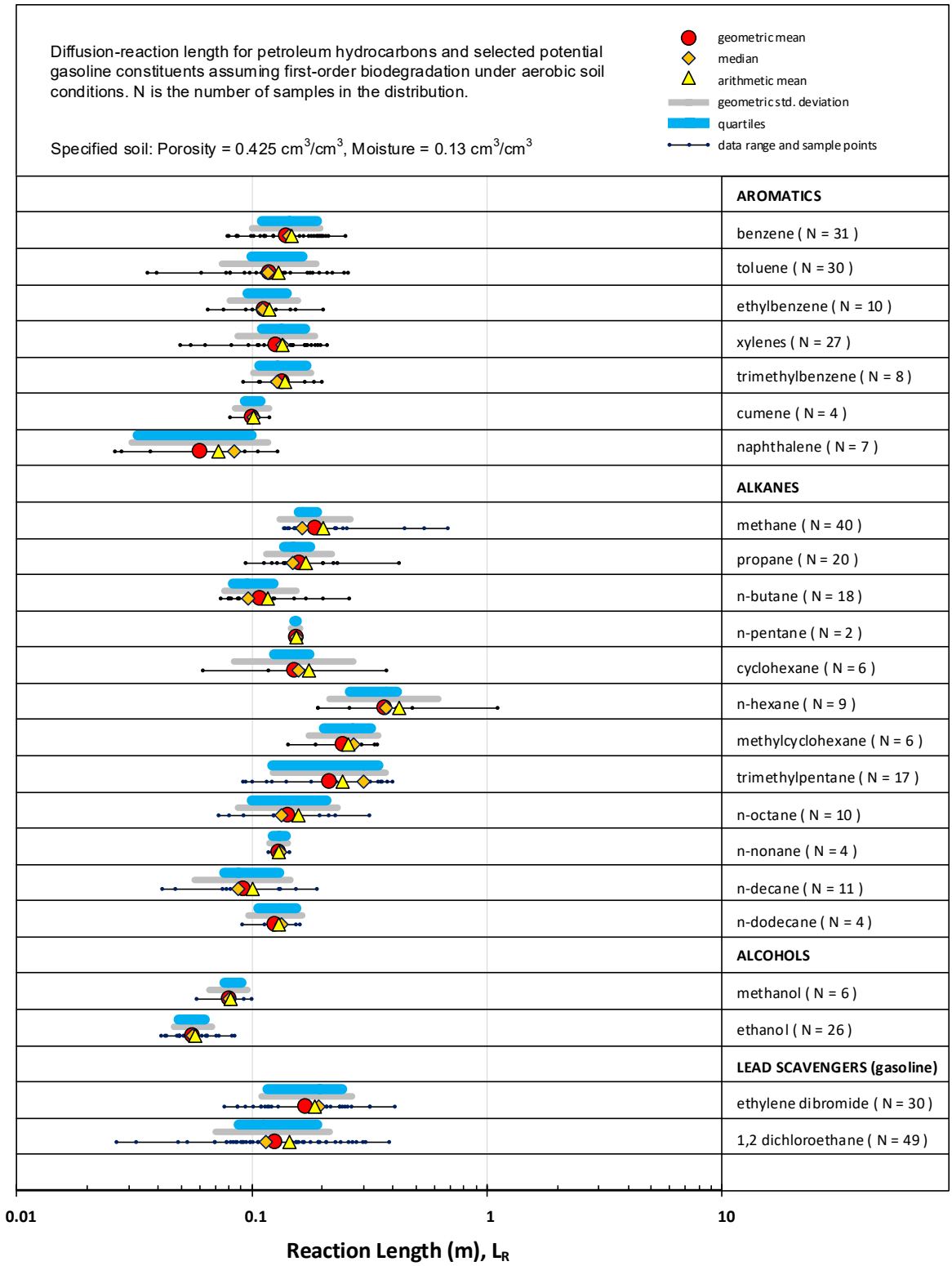


Figure H-2. Diffusion-reaction length for various petroleum hydrocarbon chemicals assuming first-order biodegradation under aerobic soil conditions. N is the number of samples in the distribution.

Source: DeVaull (2011), used with permission.

H.3.2 Interpretation of Degradation Rates

The first-order water-phase degradation rates in Table H-2 may be related to the attenuation in PHC vapor concentrations using several soil parameters and properties. Assuming a one-dimensional transport model that incorporates diffusion and first-order biodegradation, with 0_2 present and far from soil surface boundaries, the hydrocarbon concentration profile decreases exponentially with distance from the source, as follows:

$$\frac{c(z)}{c(z-0)} = exp\left(-\frac{z}{L_R}\right) \qquad \text{with} \qquad L_R = \sqrt{\frac{D_{eff} \cdot H}{\theta_w \cdot k_w}}$$

As a physical value, L_R is a *diffusion-reaction distance*, or the distance for the PHC vapor concentration to decrease to exp(-1) [~ 0.37] of its original value. This distance depends on the soil moisture, $\theta_{w\text{-}soil}$, effective diffusivity in the soil, D_{eff}, and Henry's Law constant, H, as well as the water-phase degradation rate, k_w. For the distributions of data, see Figure H-2 (assuming first-order biodegradation under aerobic soil conditions). The diffusion-reaction distance is calculated with the following assumptions:

- Water-phase degradation rate in Table H-2
- Nominal soil moisture, $\theta_{w\text{-}soil}$ = 0.13 cm^3/cm^3 (selected midpoint of 0.039 to 0.22 range)
- Nominal soil porosity, $\theta_{T\text{-}soil}$ = 0.425 cm^3/cm^3 (selected within the 0.36 to 0.49 range) chemical-specific parameters at reference temperature (from 20°C to 25°C)
- Effective diffusivity, D_{eff}, from the Millington-Quirk expression (Jury et al. 1983)

The calculated diffusion-reaction distances for the defined soil conditions are shown in Figure H-2.

In this specific example, diffusion-reaction lengths for many PHCs are on the order of 10 to 20 cm. All else equal, wetter soils tend to yield smaller reaction lengths. With this range of diffusion-reaction length, concentrations would decrease by approximately three to five orders of magnitude in 100 cm [exp(-5) to exp(-10)]. A broader range of reaction lengths, calculated for varied soil conditions, are presented by DeVaull (2007).

The reaction rates in Table H-2 are tabulated for air-connected soils. Observed water-phase rates will be slower in wetter soils ($\theta_{w\text{-}soil}$ < 0.20), because of effects of diffusion-limited reaction at the soil matrix pore scale (Thiele 1939; Atkinson 1968; Bosma et al. 1997; Hesse et al. 2010). Aerobic degradation rates in very wet soils are more difficult to generally quantify, as limits may

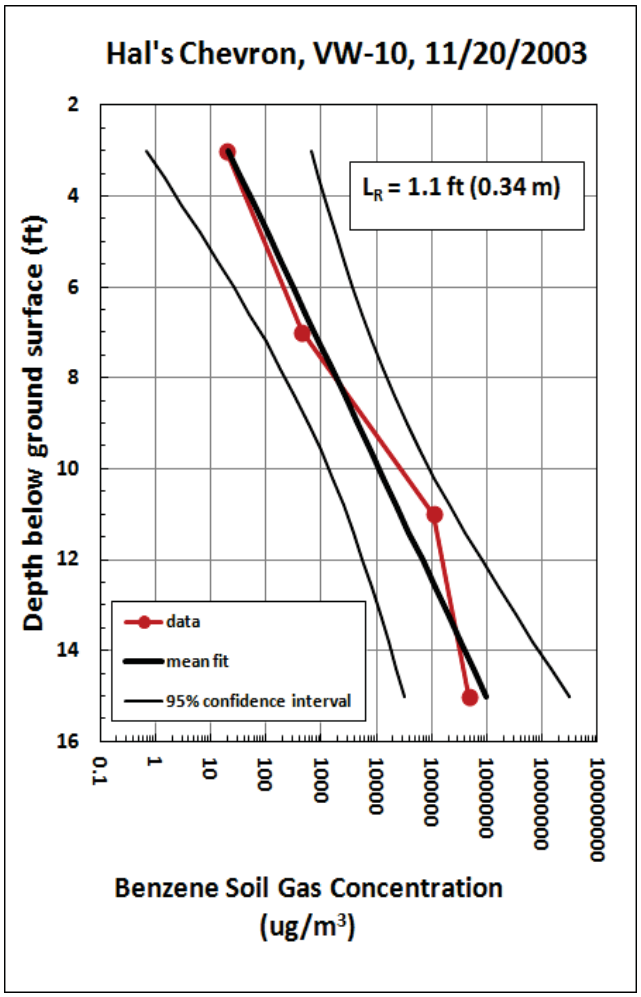


Figure H-3. Comparison of measured soil vapor to a fitted value of diffusion-reaction length (L_R).

Source: Based on data included in USEPA (2013c), used with permission.

be due to depletion of either or both hydrocarbon and O_2 at the soil matrix pore scale.

Diffusion-reaction length can be directly estimated from measured soil vapor profiles. An example is illustrated in **Figure H-3**, including measured soil vapor data and a regression fit to the exponential profile. The concentration data in **Figure H-3** decrease over four orders of magnitude in 12 feet; the fitted diffusion-reaction length L_R is 1.1 foot. More succinctly, between two measured data points, the equation for L_R is:

$$L_R = \frac{-(z_2 - z_1)}{\ln(c_2) - \ln(c_1)}$$

The estimation of water-phase degradation rate k_w from L_R requires more site-specific parameters (see the equation for fitted diffusion-reaction length above).

H.3.3 Limits to First-Order Aerobic Biodegradation Model

A first-order degradation model (and the rate constants in **Table H-2**) would apply when O_2 is present in excess throughout the reaction zone and there are no biomass limitations, which can sometimes occur at high hydrocarbon concentrations where a zero-order model may be a better approximation. Biomass limitations are not often directly observed for PHCs; concentrations of dissolved PHCs that would reach this limit often drive soil conditions anaerobic, and therefore the aerobic degradation rates would not apply. Limiting O_2 conditions may be included in models as an externally imposed limit (API 2010), in the BioVapor model, or through a more complex rate parameter, such as dual-Monod kinetics. These O_2 limitations may also include competing O_2 requirements from multiple fuel compounds.

Observed aerobic degradation rates may also sometimes be limited by the ratio of active biomass concentration to water-dissolved PHCs per unit volume of soil. This situation is not often directly observed for PHCs; concentrations of dissolved PHCs that would reach this limit are often anaerobic, and therefore the aerobic degradation rates would not apply. Biomass-limited degradation may occur for higher concentrations of ethanol, which is miscible in water.

Aerobic biodegradation reaction rates for PHCs are generally much faster than anaerobic rates, and therefore attenuation due to anaerobic degradation may be neglected. Under methanogenic conditions, methane and carbon dioxide gas may be generated from released petroleum, soil organic matter, or from other sources, including released ethanol. If the release is very large this gas generation may induce subsurface advective gas flow similar to that often observed at municipal landfills. Advective gas flow is inferred to have occurred at some refinery sites with large releases.

H.4 Case Examples

This section includes examples of biodegradation model applications using the BioVapor model v2.0, 8 January 2010 (API 2010). Model applications include the following:

- Case 1. A comparison of source-to-indoor-air attenuation factors (AFs) for multiple sites.
- Case 2. An application using measured soil vapor profile data where no building exists.
- Case 3. An application using measured soil vapor profile data under a building.

In addition, three comprehensive site case examples are discussed, illustrating the role of modeling within the greater context of investigating the site and interpreting the site data:

- Case 4—Application to Stafford Township, New Jersey

- Case 5—Application to Perth, Western Australia
- Case 6—Effect of Sealing a Building Foundation for Aerobically Degradable and Nondegradable Chemicals

H.4.1 Case 1—Comparison of Source to Indoor Attenuation Factors, Multiple Sites

Measured indoor air to source vapor concentration ratios for PHC compounds are available for a number of sites. The consolidated values in Table H-3 (Hers et al. 2003) show cases where a separation distance exists between a primary vapor source (LNAPL) and the bottom of a building foundation, source vapor concentrations are significantly greater than indoor air concentration, the quality and quantity of characterization data are reasonable, and indoor air impacts are readily differentiated from background levels.

The tabulated cases show source-zone soil vapor concentrations for benzene ranging up to 0.6E+6 µg/m^3 for vapors from gasoline; the Chatterton site is a hydrocarbon solvent release site with up to 15E+6 µg/m^3 benzene vapor concentrations. All of the measured AFs are for vapor sources originating from residual LNAPL near (3 m or less) a building foundation. Measurement of the ratios for residual sources at greater distances, or which are partially weathered and depleted in volatile chemicals, will generally be limited to upper-bound estimates (<) by the minimum measurable indoor air background limit or detection limit.

No cases are included in Table H-3 for vapors originating from groundwater sources. The authors are unaware of any documented and verified cases of subsurface to indoor air impacts from dissolved PHC chemicals in groundwater to indoor air where a separation distance exists between the primary vapor source (groundwater) and the bottom of a building foundation.

Table H-3. Measured source to indoor air vapor concentrations, Case 1—Multiple Sites.

Site Identifier and Chemical Compound	Source Vapor Concentration (µg/m3)	Source to Foundation Separation Distance (m)	Indoor Air to Source Vapor Concentration Ratio (--)
Virginia (Fan and Quinn 2000)			
Benzene	410,000	0.5	8.3E-6
Chatterton (Hers and Zapf-Gilje 1998; Hers et al. 2002)			
Benzene	15,000,000	1.4	5.3E-7, <4.0E-7 to <9.9E-5
Toluene	20,000,000	1.4	1.9E-6, <5.9E-7 to <1.3E-4
Paulsboro (Laubacher et al. 1997)			
Benzene	576,000	2.74	<1.6E-6
Alameda (Fischer et al. 1996)			
Benzene	200,000	0.7	<9.0E-6
Isopentane	28,000,000	0.7	<9.0E-7
Stafford (Sanders and Hers 2006; Sanders et al. 2004)			
Benzene	600,000; 390,000	1.65; 2.9	<8.3E-6; <5.1E-6
Toluene	1,100,000; 540,000	1.65; 2.9	4.2E-5; 5.9E-6
2,2,4-Trimethyipentane	1,900,000; 2,400,000	1.65; 2.9	2.3E-4; <8.3E-7
Cyclohexane	1,100,000; 710,000	1.65; 2.9	7.1E-5; <2.8E-6

Notes: attenuation factors are indicated as 'less than' (<) if indoor air concentrations are below background levels or detection limits.

Saturated benzene vapor concentration above gasoline LNAPL (of 1% w/w benzene) is approximately 3.2E+6 µg/m^3 (at 20°C). With an indoor air background limit or detection limit in the range of 0.3 to 3 µg/m^3, the minimum physically measurable indoor air to source vapor concentration ratio is in the range of approximately 1.0E-7 to 1.0E-6. Dilution of the saturated source vapor concentration raises this minimum limit. The actual minimum measured value in the table is 5.3E-7, for the Chatterton site, at which the LNAPL composition is >1% w/w benzene.

For comparison with the data set, the BioVapor model v2.0, 8 January 2010 (API 2010) was run with default residential assumptions, a range of source to foundation separation distances, and a selection of aerobic depths. The model results, for benzene, are plotted in Figure H-4 in comparison with the tabulated indoor to source attenuation data.

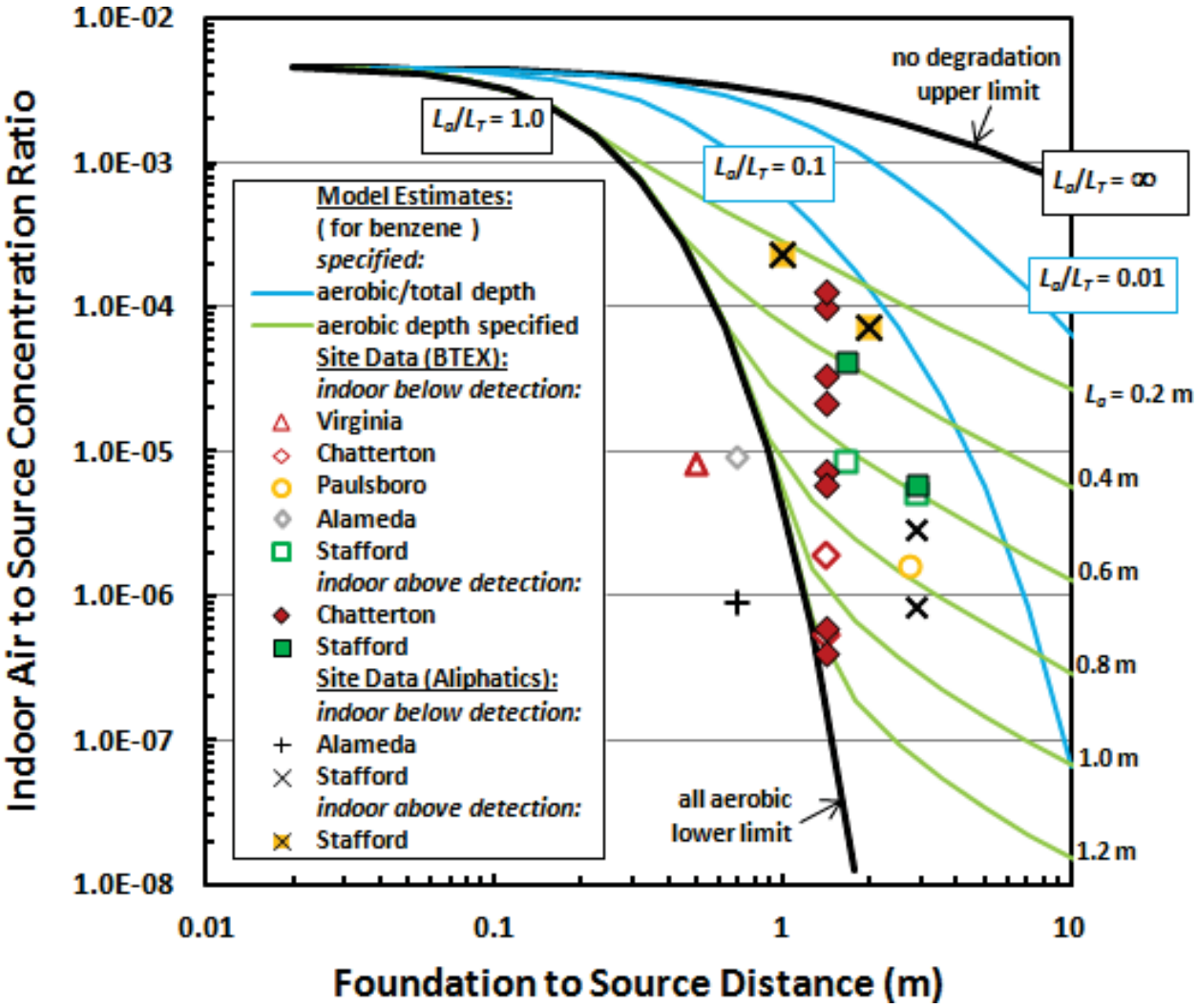


Figure H-4. Comparison of measured indoor air to source vapor (benzene) concentrations to BioVapor model estimates. Case 1—Multiple Sites.

This is a qualitative comparison of the model to data. The agreement is reasonable. All of the measured data, which are not limited by detection or background, fall between the lower and upper bounds of the model estimates. The sensitivity of decreased attenuation to increased aerobic depth is also seen in the figure. A variation in aerobic depth from 0.2 to 1.2 m is sufficient to bound all of the measured site data by the model estimates. Further refinement could be included in this comparison by including additional measured site-specific parameters in the modeled estimates. The modeled data in Figure H-4 is for

benzene; other light aromatic chemicals, including toluene, ethylbenzene, and xylenes show very similar behavior.

The chemicals in Table H-3 include both aromatics (benzene, toluene) and aliphatics (isopentane, 2,2,4-trimethylpentane, cyclohexane). The measured indoor air to source vapor concentration ratios for some of the aliphatic chemicals are up to approximately an order of magnitude larger than those for the aromatic chemicals in the same scenario. With the BioVapor model, aliphatic chemicals also show larger indoor to source concentration ratios than benzene for the same scenario parameters. This is consistent with qualitative observations from the data set in Table H-3. A direct comparison and plot of the BioVapor model results for aliphatic chemicals is not shown here, as the data are too sparse to draw more general conclusions.

H.4.2 Case 2—Soil Vapor Profile Comparison, Beaufort, South Carolina

The BioVapor model can be used to estimate the aerobic depth and VO_2 profile from the coupled O_2 demand due to summed soil respiration and hydrocarbon degradation. This section shows a comparison of these estimates to a comprehensive set of measured soil vapor profile data from a specific site, with LNAPL at depth, under an open ground surface.

H.4.2.1 Site Data Description/Methodology

Field measurements were made at up to nine soil vapor points and two groundwater depths along a vertical profile in an approximately 3.3-m vadose zone at a gasoline release site near Beaufort, South Carolina (Lahvis et al. 1999). Analysis included fixed gases (O_2, CO_2), hydrocarbon vapor species (benzene, toluene, ethylbenzene, mixed xylenes [BTEX], cyclohexane), and grouped hydrocarbon vapors (C6–C9 aliphatics, C6–C9 aromatics). Aqueous-phase chemical concentrations were measured below the water table. Continuous soil cores were analyzed for porosity, moisture content, air-filled porosity, and diffusion rates as a function of air-filled porosity. A numerical model calibrated with the measured field data, including site-specific soil heterogeneity, was developed and applied in estimating depth-dependent zero-order reaction rates.

H.4.2.2 Modeling Discussion

The measured soil vapor profile data are compared to estimates made using the BioVapor model v2.0, 8 January 2010 (API 2010). Measured soil moisture and porosity profiles show highly varied soil moisture in the deeper profile, from 0 to 43 cm above the water table in a capillary fringe, and relatively uniform air porosity in the shallower zone, from 43 cm to 332 cm above the water table. The lowest 43 cm are not included in the comparison to the BioVapor model. Source vapor concentrations in the model/data comparison are specified at the 43 cm (above the water table) depth.

For depths below 43 cm (not included in the BioVapor modeling), ratios of chemical-specific concentration relative to that at 43 cm are plotted in Figure H-5. The measured

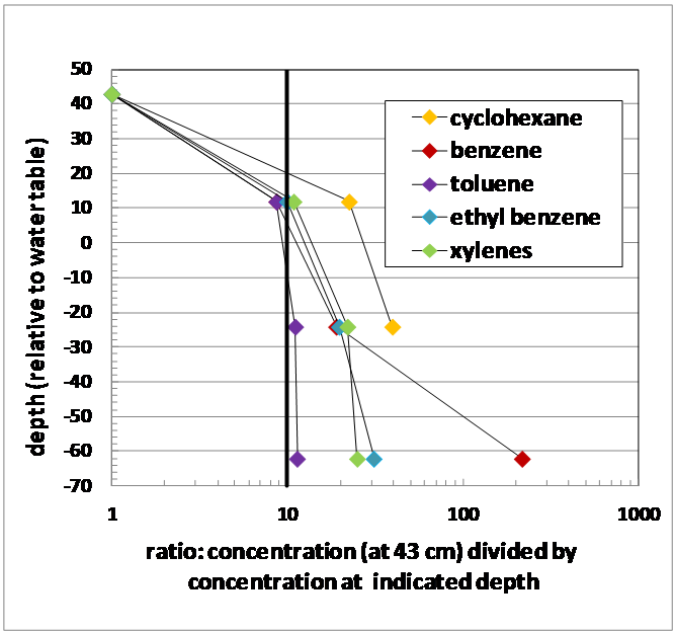


Figure H-5. Ratio of concentration at 43 cm depth divided by concentration at indicated depth for measured chemical species. Data points are connected to aid visualization. Case 2—Beaufort.

values include both soil vapor and water concentration (below the water table). The water concentrations are all converted to consistent vapor-phase concentrations using the Henry's Law coefficient in the paper. For data below the water table, the ratios (compared to the 43 cm datum) are at least a factor of 10 or greater. The BioVapor model manual suggests a factor of 10 for this ratio.

Model parameters, other than those varied from the default BioVapor model values, are shown in Table H-4. The database of properties, parameters, and degradation rates included with the BioVapor model are otherwise applied. Results of the modeling, compared with measured data are included in Figure H-6.

The comparison of the estimated measured profiles of O_2 and the speciated chemical concentrations to the model is very favorable. Differences in the speciated concentrations are noted principally at low measured vapor concentrations (<1 mg/m^3), which are near the detection level, for xylenes and toluene, in this study. The model indicates that O_2 penetrates to the modeled depth (43 cm) consistent with the data.

Table H-4. BioVapor model parameters, Case 2—Beaufort.

Parameter	Value
0_2 Surface Boundary Condition	
Earthen Floor Foundation (e.g., Specify O_2 Surface Concentration)	
Building Parameters	
Airflow Through Basement Foundation, Q_s(cm^3-air/sec) Note: A very high value is chosen, such that foundation resistance is negligible.	8,333.3
Soil Parameters	
Soil Porosity θ_T (cm^3/ cm^3) Note: Arithmetic average (Lahvis et al. 1999) Table 2, 12 to 332 cm depth range	0.3846
Soil Water Content $\theta_{w\text{-}soil}$ (cm^3/ cm^3) Note: Arithmetic average (Lahvis et al. 1999) Table 2, 55 to 332 cm depth range, above capillary fringe	0.0919
O_2 Concentration Under Foundation $C_{02\text{-}e}$ (%) Note: no foundation layer, atmospheric O_2 level is specified	21
Annual Median Soil Temperature T (°C) Note: (Lahvis et al. 1999).	23
Depth to Source (from bottom of foundation) L_T (cm) Note: depth above capillary fringe (332–43 cm)	289
Soil organic carbon fraction f_{oc} (g-oc/g-soil) Note: not measured, see discussion	0.0005
Source Vapor Concentration (at 43 cm depth)	**(mg/m^3)**
Benzene	16.7
Toluene	623
Ethylbenzene	59.2
Xylenes	287
Cyclohexane	102
Other Aliphatic Hydrocarbons (as reported, minus cyclohexane)	388
Other Aromatic Hydrocarbons (as reported, minus summed BTEX)	324.1

Note: BTEX = benzene, toluene, ethylbenzene, and xylenes.

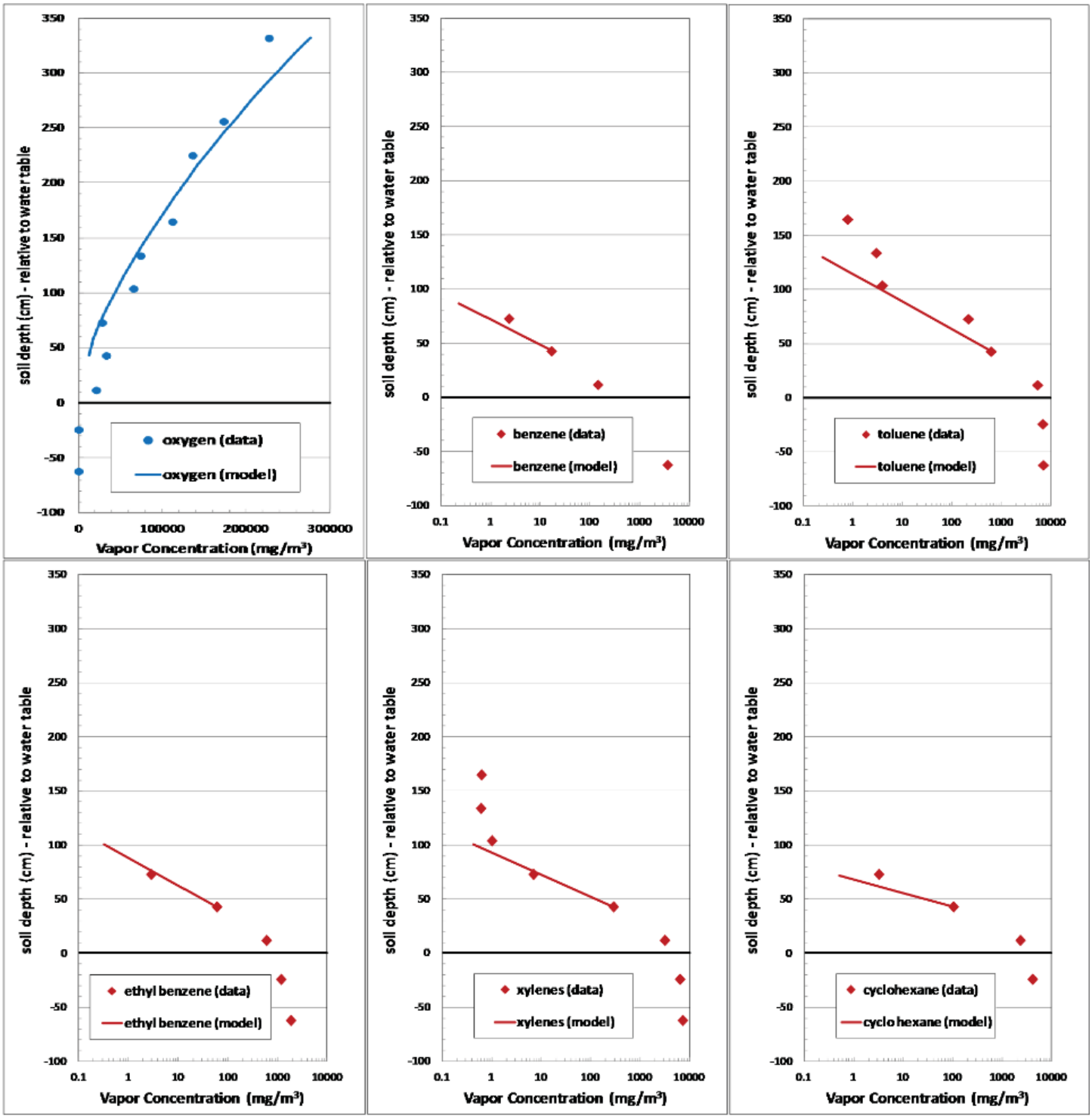


Figure H-6. Comparison of measured data to model estimates, Case 2—Beaufort.

The comparison of the estimated measured profiles of O_2 and the speciated chemical concentrations to the model is very favorable. Differences in the speciated concentrations are noted principally at low measured vapor concentrations (<1 mg/m^3), which are near the detection level, for xylenes and toluene, in this study. The model indicates that O_2 penetrates to the modeled depth (43 cm) consistent with the data.

O_2 concentration in the model is the result of the sum of demand from the individual chemicals, along with demand from baseline soil respiration. Modeled baseline respiration in the BioVapor model is presumed proportional to soil organic carbon concentration, which was not measured in the study. The specified soil organic carbon level (f_{oc} = 0.0005 g/g-oc), and proportionate baseline soil O_2 demand in this comparison, is a factor of 10 less than the default BioVapor value (f_{oc} = 0.005 g/g-oc). The sensitivity of aerobic depth, as a function of varied soil organic carbon, is shown in Table H-5.

Table H-5. Sensitivity of aerobic depth versus soil organic carbon, Case 2—Beaufort.

Specified Soil Organic Carbon Level f_{oc}(gIg-soil)	Modeled Aerobic Depth (cm)	0_2 Demand Due to Baseline Respiration (%)
0.005	246.6	97.1
0.001	289	58.6
0.0005	289	41.4

H.4.2.3 Summary

- Overall, the model to data comparison is good.
- The default soil organic carbon and the dependent baseline soil respiration rate in the BioVapor model are higher than the data suggest in this case. Using the default soil respiration rate overestimates O_2 demand and overestimates vapor transport to shallower soil depths compared to the measured data.
- The BioVapor model user's guide suggests a factor of 0.1 in relating measured groundwater concentrations to soil vapor concentrations above the capillary fringe (i.e., soil vapor concentration predicted from Henry's Law constant is multiplied by 0.1). Data for this site shows this factor to be reasonable or conservative (overestimating soil vapor concentrations) in this case.

H.4.3 Case 3—Soil Vapor Profile Comparison, Alameda, California

The BioVapor model can be used to estimate the aerobic depth and soil vapor O_2 profile from the coupled O_2 demand due to summed soil respiration and hydrocarbon degradation. This section shows a comparison of these estimates to a comprehensive set of measured soil vapor profile data from a specific site, with LNAPL at depth, under a concrete-slab building foundation.

H.4.3.1 Site Data Description/Methodology

Soil vapor was measured at multiple sample points below and adjacent to a slab-on-grade building above a residual aviation gasoline source (Fischer et al. 1996) to a depth of approximately 0.65 m. Vertical profiles were measured and reported for methane, 2-methyl butane (isopentane), O_2, and CO_2. Soil vapor diffusion rates were estimated using SF_6 tracer gas.

H.4.3.2 Modeling Discussion

The measured soil vapor profile data were compared to estimates made using the BioVapor model v2.0, 8 January 2010 (API 2010). The residual hydrocarbon smear layer suggests a 0.65-m source depth below the on-site building; vapor concentrations at depths greater than 0.65 m are near constant. The slab-on-grade building includes a foundation thickness of approximately 0.10 cm.

While other chemicals were measured at the site, the dominant source vapor constituents consist of methane and isopentane. Shallow O_2 concentrations below the slab are near ambient levels (21% v/v); airflow either through or around the foundation slab is apparently not limiting the O_2 concentration in shallow soils. Effective airflow through the foundation is estimable from SF_6 tracer concentration measurements across the foundation. With indoor to subsurface SF_6 tracer concentration ratios between 0.00025 and 0.00045, an air ER of 1.5 /hr, and a building volume of 50 m^3, effective airflow through the 50 m^2 foundation is in the range of 0.6 to 1.1 L/min, consistent with a concrete slab-on-grade building.

Applied BioVapor model parameters are shown in Table H-6. The database of properties, parameters, and degradation rates included with the BioVapor model are otherwise applied.

Table H-6. BioVapor model parameters.

Parameter	Value
O_2 Surface Boundary Condition	
Earthen Floor Foundation; 0_2 concentration (as measured) is specified below the foundation	
Building Parameters	
Airflow Through Basement Foundation, Q_s(cm^3-air/sec) Note: Value is based on measured isopentane concentration ratio across the foundation	833.3
Soil Parameters	
Soil Porosity θ_T (cm^3/cm^3) Note: Measured arithmetic average, 20–62 cm depth range	0.368
Soil Water Content $\theta_{w\text{-}soil}$ (cm^3/cm^3) Note: Measured arithmetic average, 20–62 cm depth range	0.152
O_2 Concentration Under Foundation $C_{02\text{-}e}$ (%) Note: atmospheric O_2 level is measured below the foundation	21
Annual Median Soil Temperature T (°C) Note: from paper	15
Depth to Source (from bottom of foundation) L_T (cm) Note: depth above capillary fringe (65–10 cm)	55
Soil organic carbon fraction f_{oc} (g-oc/g-soil) Note: as measured average, 20–62 cm depth range	0.0034
Soil bulk density (g/cm^3) Note: as measured average, 20–62 cm depth range	1.6
Source Concentration (at 65 cm depth)	**(mg/m^3)**
Methane	80,000
Isopentane	55,000
N-pentane	6,800
C6-7 Aliphatic (sum of 2,3-dimethyipentane and 4-methyi-hexane)	5,500
Benzene	200
Toluene	200

Results of the modeling, compared with measured soil vapor data, are shown in Figure H-7. For the base case, the BioVapor model tends to underestimate O_2 penetration and underestimate both methane and isopentane degradation. As a check on model sensitivity, the effective diffusion coefficient in the model

was divided by factors of 2.5 and 5. The results are included in the figure and may indicate a potential overestimation of diffusion rate in the model.

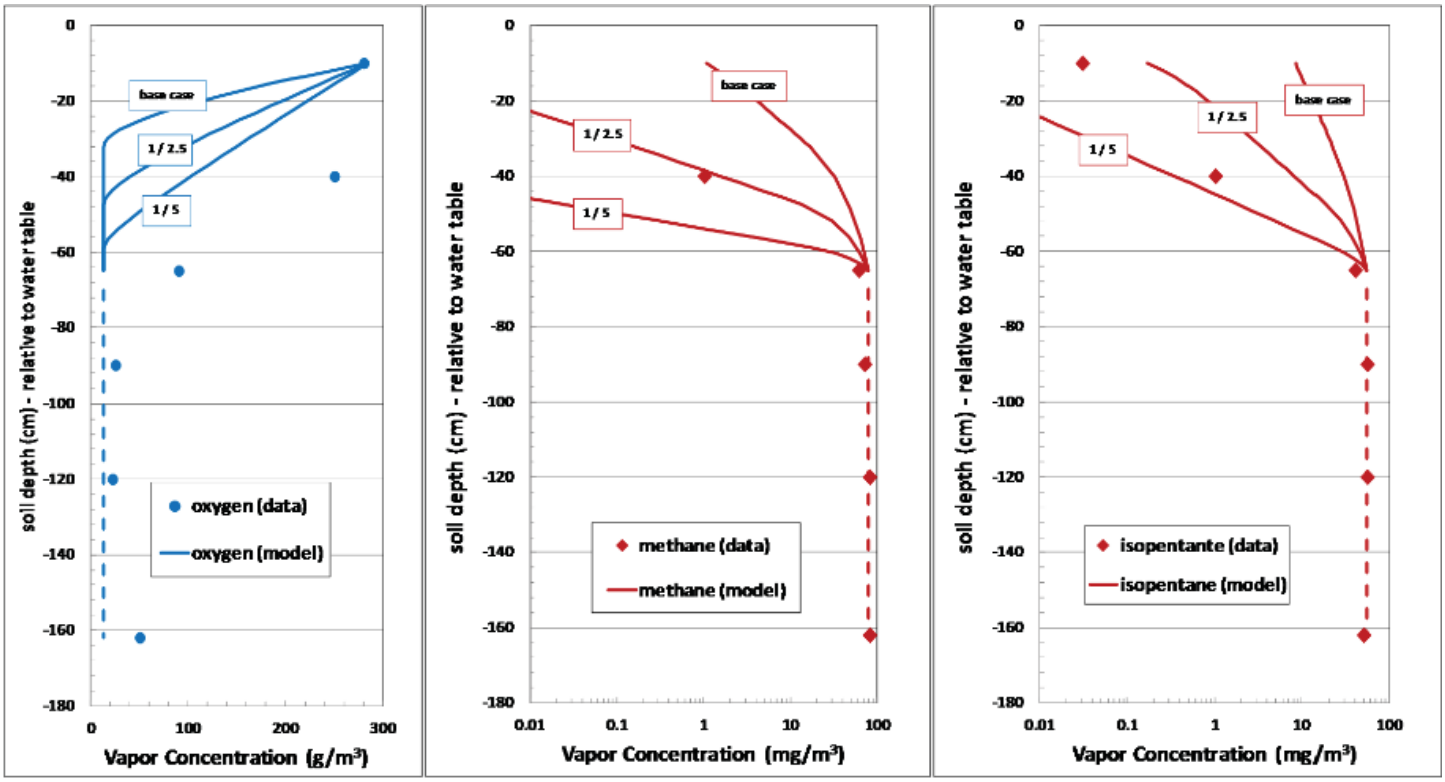


Figure H-7. Comparison of the BioVapor model to measured data below the building. The base case shows results for the applied parameters. Results presuming a lower effective diffusion coefficient, by factors of 2.5 and 5, are also shown in the plots.

H.4.3.3 Summary

- Overall, the model overestimates shallow concentrations of PHCs.
- Greater O_2 penetration is seen in the data than the model suggests.
- The paper includes data measured below an adjacent asphalt forecourt, which is very similar to that shown below the building and is therefore not included here.
- Variation between the model and the data suggests a zone may exist very near the foundation with enhanced mixing or diffusion (due to the foundation), compared to deeper levels.

H.4.4 Case 4—Application to Stafford Township, New Jersey

This example shows the use of the BioVapor model in aiding the interpretation of site assessment data. An early version of the BioVapor model V2.0 beta 4, 2 November 2009 (API 2010) was applied in the model estimates.

All the assessment data are published and available (NJDEP 2005b; Sanders and Hers 2006; Sanders et al. 2004). Extensive site information is included, including soil vapor and indoor air data. Parameters and results for a numerical VI model are included in the reports. These reported model parameters are applied in running the BioVapor model in this example.

H.4.4.1 Scenario Description

The site scenario is a gasoline leak from an underground gasoline storage tank site. The leaking tank has been removed. Downgradient soil and groundwater are affected. The nominal groundwater depth below ground surface is 3.3 m.

Buildings and residences are above the affected groundwater zone, and some have basements to depths of 1.8 m below ground surface, leaving a separation distance between basements and groundwater of approximately 1.65 m. Shallow soils are sand. The site is in southern coastal New Jersey, USA.

H.4.4.2 Risk Management and Site Investigation

This investigation was conducted under the direction of the New Jersey Department of Environmental Protection (NJDEP) with their contractors. It is used here as an example of model/data comparisons. 0ccupied commercial and residential buildings were included in the investigation. The investigation, analysis, and interpretation, as discussed in the cited reports, was conducted as a research project to better understand subsurface to indoor air VI issues and risks. Typical VI investigations would not be as detailed or extensive.

H.4.4.3 Criteria Levels

The residential indoor air criteria concentration (µg/m^3) levels applied in this example are from the responsible regulatory agency (NJDEP). An extensive summary has been compiled in the referenced report of background indoor air concentrations. Site-specific background values are used for comparison in this example. The values are as shown in Table H-7.

Table H-7. Indoor air criteria and background concentrations, Case 4—Stafford.

Chemical	Indoor Air Screening Level Concentration (µg/m^3)	Indoor Air Screening Level Concentration (ppbv)	Background Indoor Air Concentration Levels (µg/m^3)	Background Indoor Air Concentration Levels (ppbv)
Benzene	2	0.6	<1.6 to 3.9	<0.5 to 1.2
Toluene	5,200	1,360	14 to 33	3.6 to 8.7
Ethylbenzene	2	0.45	<2.2 to 5.7	<0.5 to 1.3
Xylenes	100	23	11 to 25	2.4 to 5.7
MTBE	9	2.5	2.3 to 9.5	0.62 to 2.6
2,2,4-Tri-methylpentane	Unavailable	Unavailable	<2.4 to 11	<0.5 to 2.3
Cyclohexane	6,300	1,800	<1.7	<0.5

Note: MTBE = methyl tertiary-butyl ether.

Source: Screening levels sourced from New Jersey Department of Environmental Protection, Site Remediation Program, Vapor Intrusion Guidance, Updated Vapor Intrusion Screening Level Tables (revised March 2013, accessed 0ctober 2014), Table 1, residential (NJDEP 2013). Background concentrations sourced from Reports on Investigation of Indoor Air Quality in Structures Located Above V0C-Contaminated Groundwater, for New Jersey Department of Environmental Protection by Golder Associates, Inc., 2005–2006 (NJDEP 2005a). Soil Vapor Intrusion—Year 1: Research Study at Stafford Township and Egg Harbor Sites, New Jersey (March 2005) (NJDEP 2005b) Table 3-15; 20°C assumed for ppbv to mg/m^3 conversion; xylenes total is sum of m-,p-,o- isomers.

H.4.4.4 Qualitative Site Evaluation

Preliminary questions and checks are listed below:

- Is the scenario consistent with conceptual model assumptions?
- Are there other relevant issues that may need to be addressed?

The qualitative criteria for identifying potential issues in VI from subsurface to indoor air and possible model exceptions include the following; answers for this specific scenario are provided for each criterion:

- **Is highly affected water or gasoline directly within or in direct contact with basement, crawl spaces, sumps, or conduits?** No, there are no basements, crawl spaces, sumps or conduits directly in contact with highly affected water or gasoline.
- **Are very large subsurface petroleum nonaqueous-phase liquid (NAPL) releases near the foundations or subsurface enclosures?** Yes. Based on the reported site data, it is evident that LNAPL is likely to be present in the immediate vicinity of several buildings on the site, at and near the water table. A screening analysis follows.
- **Is there confined lithology and pressure-driven vapor flow where pressure may originate from rising or falling water tables and/or methane gas generation?** No.

For VI estimates from hydrocarbons, estimates of O_2 demand (and O_2 presence in the subsurface) are needed.

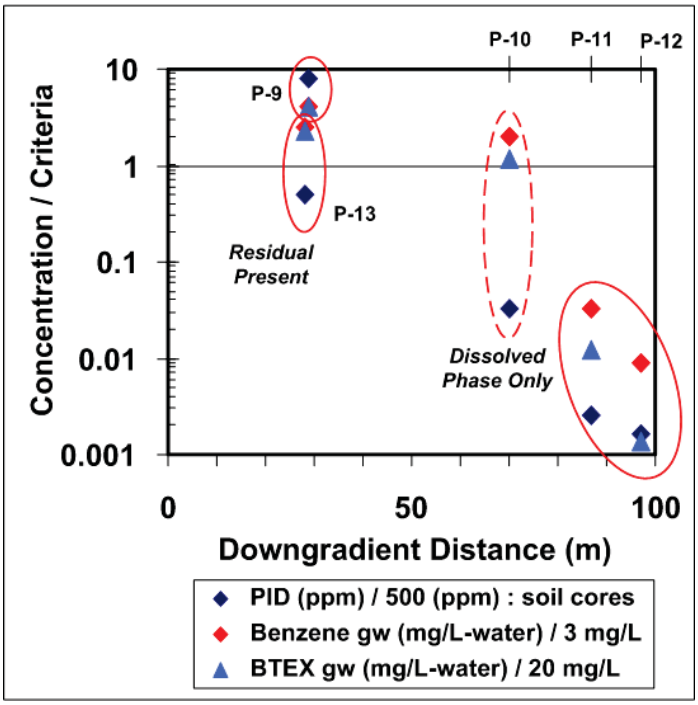
- Baseline O_2 demand in sand soil is low (site measured f_{oc} = 0.006 g-oc/g-soil).
- Additional O_2 demand originates from PHC vapors evolved from groundwater and from residual gasoline.

Relevant criteria for determining either the confirmed or suspected presence of an LNAPL, as tabulated and discussed in (ASTM International 2006a), can include any of the following direct and indirect methods:

- Observed LNAPL in wells or samples; positive field-screening tests (for example, paint filter test, dye test, shake test); fluorescence indicative of LNAPL
- Measured concentrations near an effective solubility (in water) or saturated vapor limit (in air); TPH levels indicative of LNAPL presence; organic vapor analyzer results
- Dissolved plume persistence and center-of-mass stability over time

If LNAPL is suspected or confirmed, establish the following:

- Confidence in adequate delineation of suspected or confirmed NAPL zones, including at the water table and in soils from the water table to the ground surface
- Presence of an aerobic soil buffer zone between NAPL vapor sources and building foundations, either through estimation or measurement
- Screening of potentially flammable vapors proximate to building foundations or subsurface enclosures



Note: BTEX = benzene, toluene, ethylbenzene, and xylenes;
PID = photoionization detector.

Figure H-8. Comparison of light nonaqueous-phase liquid screening values to site data, Case 4—Stafford.

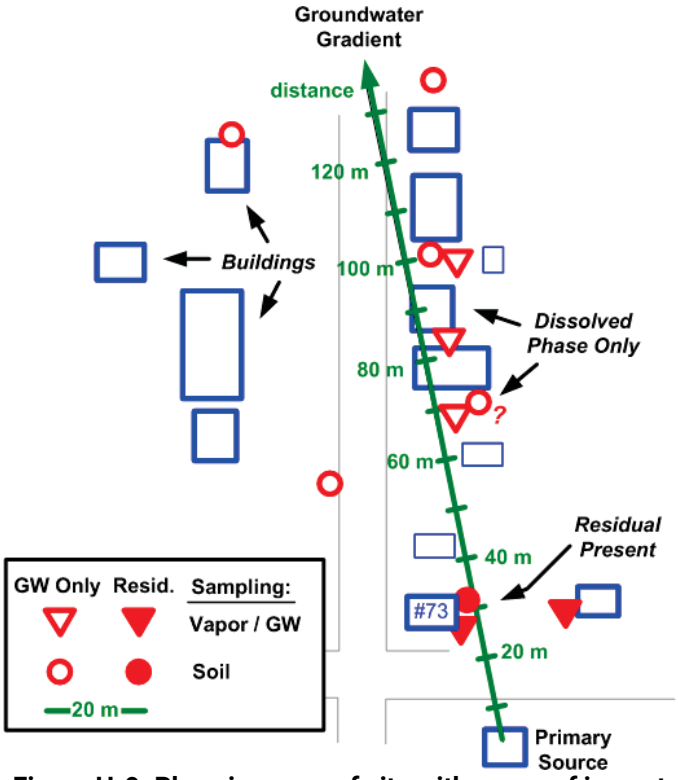


Figure H-9. Plan view map of site with zones of impact indicated, Case 4—Stafford.

Based on the reported site data, it is evident that LNAPL is likely to be present in the immediate vicinity of several buildings on the site, at and near the water table. Figure H-8 is a comparison of ratios of site data to a number of criteria based on ASTM E2531-06 (ASTM International 2006a) (water-dissolved and vapor concentrations); there are other relevant criteria (soils concentration data, for example). The LNAPL screening values chosen here are nominally representative for gasoline and may vary for other petroleum products and compositions.

These screening criteria are used on a plan view map of the site, shown in Figure H-9. This illustrates a near-zone region with LNAPL impacts likely under several buildings and a far-zone region with dissolved-phase-only groundwater impacts underneath buildings. Open points on the plan view map indicate vapor sources from groundwater only (labeled "GW only"); closed points indicate the vapor source is likely to originate from residual PHC or LNAPL (labeled "Resid.").

H.4.4.5 Modeling and Site Data Interpretation

Chemicals of Interest

A database of chemicals is included in the BioVapor model and may be edited as appropriate. If selected measured chemicals of potential interest in vapor and groundwater at the site are not included in the BioVapor model database, they may be added using available parameters. Indoor air criteria concentrations (µg/m^3), as available from the local agency (NJDEP), were entered into the BioVapor chemical database.

Table H-8. Applied model parameters, Case 4—Stafford.

Case A	Case B	Symbol	Parameters
Logic and Control Parameters			
			O_2 conditions (slab or basement foundation present, ambient O_2 in air)
Vapor Inhalation Exposure Parameters			
			not used; directly compared with indoor concentration criteria
Building Parameters and Geometry			
421	421	W_b	(cm) building width
867	867	L_b	(cm) building length
365,007	365,007	$W_b \cdot L_b$	(cm^2) building footprint area
213	213	H_b	(cm) building height
165	165	D_b	(cm) depth to base foundation below grade
98.41	98.41	L_{mix}	(cm) enclosed-space volume/infiltration area ratio, or mixing height = Q_b / (Ab · ER)
11.28	11.28	ER	(1/day) enclosed-space air exchange rate
77,746,491	77,746,491	V_b	(cm^3) building volume = $W_b \cdot L_b \cdot H_b$
10,150.24	10,150.24	Q_b	(cm^3/sec) building airflow = $V_b \cdot$ ER
0.609	0.609	Q_b	(m^3/min) building airflow
790,047	790,047	Ab	(cm^2) subsurface foundation area in contact with soil = $W_b \cdot L_b + D_b \cdot 2 \cdot (W_b + L_b)$
10	10	L_{crack}	(cm) enclosed-space foundation or wall thickness
1	1	W_{crack}	(cm) crack width - perimeter crack
2,576	2,576	A_{crack}	(cm^2) crack area = $W_{crack} \cdot 2 \cdot (W_b + L_b)$
0.00326	0.00326	η	(cm^2-cracks/cm^2-total area) foundation crack fraction = A_{crack} / Ab
2	5.98	Q_s	(L/min) soil vapor advection rate
33.33	99.7	Q_s	(cm^3-air/sec) convective airflow through basement foundation
33.33	99.7	Q_f	(cm^3-air/sec) convective airflow under basement foundation, $Q_f = Q_s$ or $Q_f > Q_s$
165	165	L_T	(cm) depth - below basement slab to groundwater depth vapor source
330	330		(cm) depth - soil surface to groundwater vapor source depth = $L_T + D_b$
Soil Parameters			
sand	sand		soil type
0.378	0.378	θ_T	(cm^3-void/cm^3-soil) soil porosity, vadose-zone soils
0.045	0.045	θ_w	(cm^3-water/cm^3-soil) soil water content, vadose-zone soils
0.378	0.378	θ_T	(cm^3-void/cm^3-soil) soil porosity, soil-filled basement cracks
0	0	θ_w	(cm^3-water/cm^3-soil) soil water content, soil-filled basement cracks
6.0E-03	6.0E-03	f_{oc}	(g-oc/g-soil) soil organic carbon fraction, vadose-zone soils
1.7	1.7	ρ_s	(g-soil/cm^3-soil) soil density - bulk
Environmental parameters			
7.5	7.5	T_{amb}	(°C) ambient temperature
760	760	P_{amb}	(mmHg) atmospheric pressure
Measured Subfoundation to Average Indoor Air Concentration Ratio			
	0.00982	c_e / c_f	(--) average measured ratio
Key:			
Specified values used in calculating other values			
Values applied in model			
Values changed from Case A to B			

Modeling and Analysis

For VI screening, this site is divided into two subunits: Subunit (1) dissolved plume only, and Subunit (2) LNAPL present or suspected.

Subunit (1) Dissolved Contaminants in Soluble Groundwater Plume

For this Subunit (1) case example, building and scenario parameters are presented in Table H-8 under Case A. The building parameters are similar to a residential building with a basement and include site-specific measured, calculated, and derived parameters. The soil parameters correspond to sand but include site-specific measured values.

A subset of the values from Table H-8 are entered into the BioVapor model, as illustrated in Table H-9.

Table H-9. BioVapor model scenario parameters, Case 4 – Stafford.

1. Oxygen Surface Boundary Condition

Slab or Basement Foundation (e.g., Specify Airflow)

2. Indoor Target Criteria

Specified Indoor Air Concentration Target

3. Exposure and Risk Factors

note: not used, as indoor air target criteria are specified

4. Building Parameters

Indoor Mixing Height	L_{mix}	98.41	cm
Air Exchange Rate	ER	11.28	1/day
Foundation Thickness	L_{crack}	10.0	cm
Foundation Area	A_b	790047	cm^2
Foundation Crack Fraction	η	0.00326	cm^3-cracks/cm^3-total
Total Porosity (Soil-filled Cracks)	$\theta_{T\text{-}crack}$	1.00	cm^3-void/cm^3-soil
Water Filled Porosity (Soil-filled cracks)	$\theta_{w\text{-}crack}$	0.00	cm^3-water/cm^3-soil
Airflow Through Basement Foundation	Q_s	33.33	cm^3-air/sec
Building Envelope Resistance	L_{mix} · ER	0.0128	cm/sec

5. Vadose Zone Parameters

Soil Porosity	$\theta_{T\text{-}soil}$	0.378	cm^3-void/cm^3-soil
Soil Water Content	$\theta_{w\text{-}soil}$	0.045	cm^3-water/cm^3-soil
Soil Organic Carbon Fraction	f_{oc}	0.006	(g-oc/g-soil)
Soil Density - Bulk	ρ_s	1.7	(g-soil/cm^3-soil)
Airflow Under Foundation	Q_f	33.33	cm^3-air/sec
Depth of Aerobic Zone Under Foundation	L_a	-	cm
O2 Concentration Under Foundation	$C_{O2\text{-}e}$	-	%
Annual Median Soil Temperature	T	7.5	°C
Baseline Soil Oxygen Respiration Rate (calculated from foc)		1.2E-07	mg-O_2 / g-sol -sec
Depth to Source (from bottom of foundation)	L_T	165	cm
Minimum O_2 Conc. For Aerobic Biodegradation		1.00	%

For the likely "(1) Dissolved plume only" portion of the site, shallow maximum groundwater concentrations are entered into the BioVapor model (Table H-10). The groundwater concentrations are in units of µg/L and a groundwater to deep soil vapor attenuation factor (across the capillary fringe) is entered as 1.

The entered groundwater concentrations are maximum values measured in the dissolved-phase portion of the plume. All values are for the same groundwater monitoring well. The entered 12,000 µg/L-water for toluene is nondetect at this well, but it is included in the source composition as it is detectable colocated with BTEX chemicals in other monitoring wells at the site. Cyclohexane is measured but not detected in any groundwater well above detection limits and is therefore not included in the source groundwater composition.

The BioVapor model results compared with applied screening-level concentrations and background concentrations are shown in Table H-11. The screening criteria concentrations are exceeded, with these model assumptions, for methyl tertiary-butyl ether (MTBE) and benzene in the biodegradation model results. The criteria are exceeded for benzene, ethylbenzene, xylenes, and MTBE in the no biodegradation model results.

Ground Water Source Chemical Concentrations

Chemical	ug/L
benzene	6.00E+03
toluene	1.20E+04
ethylbenzene	2.20E+03
xylenes (mixed isomers)	3.30E+03
MTBE	3.10E+05
Total Entered Hydrocarbon Concentration (ug/L)	3.34E+05
Attenuation Factor	1.0

Table H-10. BioVapor model source groundwater concentrations, Case 4—Stafford.

Table H-11. Comparison of model results to indoor air criteria using groundwater data for dissolved contaminants in soluble groundwater plume, Case 4—Stafford.

Chemical	Groundwater Source Concentration (µg/L-water)	Predicted Soil Vapor Source Concentration (µg/m^3-air)	Predicted Indoor Air Concentration (µg/m^3-air)	Indoor Air Concentration Criteria (µg/m^3-air)		Upper Background Concentration (µg/m^3-air)	
Model Results with Biodegradation Neglected					**Exceeded?**		**Exceeded?**
Benzene	6,000	615,000	1,120	2	Y	3.9	Y
Toluene	12,000	1,340,000	2,430	5,200		33	Y
Ethylbenzene	2,200	262,000	444	2	Y	5.7	Y
Xylenes (total)	3,300	259,000	428	100	Y	25	Y
MTBE	310,000	4,390,000	7,640	9	Y	9.5	Y
Model Results with Biodegradation Included					**Exceeded?**		**Exceeded?**
Benzene	6,000	615,000	2.73	2	Y	3.9	
Toluene	12,000	1,340,000	7.16	5,200		33	
Ethylbenzene	2,200	262,000	1.13	2		5.7	
Xylenes (total)	3,300	259,000	0.292	100		25	
MTBE	310,000	4,390,000	3,090	9	Y	9.5	Y

Note: MTBE = methyl tertiary-butyl ether.

In comparison with the local upper background concentration values, the no biodegradation model results indicate all of the tabulated chemicals would be significantly above background concentrations in indoor air.

The biodegradation model results indicate that MTBE would be significantly above background, with the remaining chemicals below background. No NJDEP screening criteria are exceeded for toluene, ethylbenzene, and xylenes in the dissolved-phase portion of the plume in the biodegradation model results. Toluene in groundwater is <12,000 µg/L-water, or nondetect due to matrix interferences (other chemicals in the same groundwater sample). Even with entered toluene groundwater source concentration of 12,000 µg/L-water, the calculated indoor criteria are met for toluene.

With the Groundwater to Deep Soil Vapor Attenuation Factor specified equal to 1, attenuation across the water-table capillary fringe is neglected in the prior modeled case. Site soil vapor has been measured above and adjacent to the groundwater samples. Comparison of maximum soil vapor values with measured maximum groundwater concentrations are shown in Table H-12 for the dissolved-phase groundwater plume.

Table H-12. Comparison of estimated (from groundwater partitioning) and measured deep soil vapor concentrations, Case 4—Stafford.

Chemical	Groundwater Source Concentration (µg/L)	Henry's Law Coefficient [at 7.5°C] (cm^3/cm^3)	Equilibrium-Calculated Soil Vapor Source Concentration ($µg/m^3$)	Measured Deep Soil Vapor Concentration ($µg/m^3$)	Ratio
Benzene	6,000	0.102	6.15E+5	<2,100	<0.003–4
Toluene	<12,000	0.112	<1.34E+6	3,300	~0.002–5
Ethylbenzene	2,200	0.119	2.62E+5	<2,800	<0.011
Xylenes	3,300	0.079	2.59E+5	<5,700	<0.022
MTBE	310,000	0.014	4.39E+6	56,000	<0.013
2,2,4-Trimethylpentane	not measured	52.7	--	1,700	--
Cyclohexane	<12,000	2.88	<3.46E+7	<2,300	--

Note: MTBE = methyl tertiary-butyl ether.

The Groundwater to Deep Soil Vapor Attenuation Factor based on measured data for these chemicals is nominally 0.01 to 0.001, or it may be smaller due to detection limits.

For the measured 2,2,4-trimethylpentane vapors, an equilibrium-calculated groundwater source concentration of 0.032 µg/L-water is estimated. This would be below detection limits in water, if measurement was attempted.

The measured concentration ratios (Table H-13) and inferred gradients from groundwater to deep soil vapor indicate that the direction of chemical flow is from groundwater to soil vapor with high confidence, for all of the tabulated chemicals measured above detection limits. The magnitude of chemical mass flow depends on resistance across the capillary fringe and possible degradation losses.

Soil Gas Source Chemical Concentrations

Chemical	ug/m^3
benzene	2.10E+03
toluene	3.30E+03
ethylbenzene	2.80E+03
xylenes (mixed isomers)	5.70E+03
MTBE	5.60E+04
trimethylpentane, 2,2,4-	1.70E+03
cyclohexane	2.30E+03

Total Entered Hydrocarbon Concentration (ug/m^3): 7.39E+04

Table H-13. BioVapor model source soil vapor concentrations, Case 4—Stafford.

The BioVapor model results can be refined by entering the measured deep soil vapor data, rather than the groundwater concentration data. Other model scenario assumptions are included in Table H-8, Case A.

Consolidated BioVapor model results for the specified source vapor concentrations are shown in Table H-14. The target indoor air concentrations are NJDEP residential screening criteria. The screening criteria concentrations are exceeded, with these model assumptions and source concentrations, for MTBE. Local upper background concentration is exceeded for MTBE.

Table H-14. Comparison of BioVapor model results to indoor air criteria, Case 4—Stafford.

Chemical	Soil Vapor Source Concentration (µg/m³-air)	Predicted Indoor Air Concentration (µg/m³-air)	Target Indoor Air Concentration (µg/m³-air)		Upper Background Concentration (µg/m³-air)	
Model Results with Biodegradation Neglected						
Benzene	2,100	3.83	2	Y	3.9	
Toluene	3,300	5.99	5,200		33	
Ethylbenzene	2,800	4.74	2	Y	5.7	
Xylenes (total)	5,700	9.43	100		25	
MTBE	56,000	97.4	9	Y	9.5	Y
Cyclohexane	2,300	2.51	6,300		<1.7	
2,2,4-Trimethylpentane	1,700	3.98	--		11	
Model Results with Biodegradation Included						
Benzene	2,100	6.87E-3	2		3.9	
Toluene	3,300	1.32E-2	5,200		33	
Ethylbenzene	2,800	8.88E-3	2		5.7	
Xylenes (total)	5,700	4.35E-3	100		25	
MTBE	56,000	37.5	9	Y	9.5	Y
Cyclohexane	2,300	6.87E-5	6,300		<1.7	
2,2,4-Trimethyipentane	1,700	8.86E-2	--		11	

Notes: Predicted indoor air concentrations noted as exceeding indoor air criteria (y) or as above local background ranges (y). MTBE = methyl tertiary-butyl ether.

Measurements of soil vapor below foundations and indoor air were collected and reported for buildings in the dissolved plume only region of the site. The building measurements included basements, the first occupied floor, and soil vapor below the building foundation. Summary results are shown in Table H-15.

Table H-15. Measured soil vapor concentrations below foundations and within buildings compared to criteria, Case 4—Stafford.

Chemical	Measured Below-Foundation Vapor (µg/m³)	Measured Indoor Vapor (µg/m³)	Indoor Air Concentration Criteria (µg/m³-air)	Indoor Background Concentration (µg/m³)
Benzene	<3–2.1	<2–3.9	2	<1.6–3.9
Toluene	36–38	13–34	5,200	14–33
Ethylbenzene	15–18	3–5.8	2	<2.2–5.7
Xylenes (mixed)	75–94	18–27	100	11–25
MTBE	<4–5.2	<2–9.6	9	2.3–9.5
Cyclohexane	<2-<4	<2	6,300	<1.7

Note: MTBE = methyl tertiary-butyl ether.

All reported indoor concentration values were either in the indoor background range, below the indoor criteria, or both. More detailed attempts at analysis of indoor concentration measurement in this example would be significantly biased by indoor background concentrations.

All below-foundation measurements were within a factor of four of the basement measurements. This low foundation to indoor concentration ratio is insufficient to confirm, with confidence, either chemical flow to indoors from below the foundation or the converse (chemical flow from indoors to below the foundation).

The analysis for the dissolved-phase portion of the site data is complete. In possible further analysis, soil vapor samples (including O_2) could be measured at vertical profiles adjacent to buildings, not through and below building foundations. The BioVapor model may be applied in examining possible greater O_2 depletion (and possibly higher hydrocarbon vapor levels) below the buildings, than adjacent to buildings. This may include the following:

- Estimates of vertical soil vapor profiles adjacent to buildings for which the open ground surface has ambient O_2 (21%v/v) and the depth from surface to vapor source is 3.3 m
- Estimates of vertical profile below buildings for which foundations are present, airflow (and available O_2 flux) may be limited below the foundation, and the depth from the foundation to the vapor source is 1.65 m

Subunit (2) Likely LNAPL Presence at Water Table

For the Subunit (2) LNAPL Present zone, maximum measured shallow groundwater concentrations, along with calculated equilibrium vapor concentrations, are included in Table H-16. The values are compared to adjacent measured deep soil vapor concentrations.

The measured Groundwater to Deep Soil Vapor Attenuation Factor for the chemicals with detectable concentrations in both deep soil vapor and groundwater is nominally near one. The concentration ratios and gradients are insufficient to establish that chemical flow is from groundwater to deep soil vapor or vice versa. The ratio is significantly higher than the nominal range of 0.01 to 0.001 seen in the prior dissolved plume only analysis.

Table H-16. Dissolved groundwater to soil vapor concentration comparison near light nonaqueous-phase liquid, Case 4—Stafford.

Chemical	Groundwater Concentration (µg/L-water)	Henry's Law Coefficient (L/L) [at 7.5C]	Calculated Equilibrium Vapor Concentration (µg/m^3)	Measured Deep Soil Vapor Concentration (µg/m^3)	Ratio Measured / Calculated
Benzene	12,000	0.102	1,224,000	660,000	0.54
Toluene	43,000	0.112	4,816,000	1,100,000	0.23
Ethylbenzene	4,200	0.119	499,800	<150,000	<0.30
Xylenes (total)	24,000	0.079	1,896,000	<150,000	<0.08
MTBE	590,000	0.014	8,260,000	5,900,000	0.71
2,2,4-Trimethylpentane	--	52.7	--	2,400,000	--
Cyclohexane	<5,000	2.88	<14,400,000	1,100,000	--

Note: MTBE = methyl tertiary-butyl ether.

Because of detection limits, groundwater measurements do not adequately quantify chemical vapor concentrations for compounds with high Henry's Law coefficients (This would potentially be an issue in areas where relatively insoluble LNAPL would be present). The high 2,2,4-tri-methylpentane and

cyclohexane vapor concentrations are therefore not detected (or measured) in groundwater. Measured soil vapor concentrations (including 2,2,4-trimethylpentane and cyclohexane) have been applied in the model.

Indoor air concentrations for these chemicals are estimated using the BioVapor model. Relevant and applicable model parameters, based on site-specific information, parameter assumptions applied by the local agency, and prior site reports are included as Case A in Table H-8. The indoor air criteria concentrations are from the local regulatory agency presuming residential building use, as in Table H-7. The applicable source vapor concentrations are shown in Table H-17.

Soil Gas Source
Chemical Concentrations

Chemical	ug/m³
benzene	6.60E+05
toluene	1.10E+06
ethylbenzene	1.50E+05
xylenes (mixed isomers)	1.50E+05
MTBE	5.90E+06
trimethylpentane, 2,2,4-	2.40E+06
cyclohexane	1.10E+06
Total Entered Hydrocarbon Concentration (ug/m³)	1.15E+07

Table H-17. BioVapor model source vapor concentrations, Case 4—Stafford.

The consolidated BioVapor model results for the specified source vapor concentrations are included in Table H-18. The screening criteria concentrations are exceeded, in the biodegradation neglected results, for benzene, ethylbenzene, xylenes, and MTBE. In the biodegradation included results, screening levels are exceeded for benzene and MTBE. The no biodegradation estimates exceed background for all chemicals in the table. For the biodegradation results, indoor concentration estimates exceed background for MTBE and 2,2,4-trimethylpentane.

Table H-18. Comparison of BioVapor model results to indoor air criteria, Case 4—Stafford.

Chemical	Soil Gas Source Concentration (µg/m³-air)	Predicted Indoor Air Concentration (µg/m³-air)	Target Indoor Air Concentration (µg/m³-air)		Upper Background Concentration (µg/m³-air)	
Model Results with Biodegradation Neglected						
Benzene	660,000	1,200	2	Y	3.9	Y
Toluene	1,100,000	2,000	5,200		33	Y
Ethylbenzene	150,000	254	2	Y	5.7	Y
xylenes (total)	150,000	248	100	Y	25	Y
MTBE	5,900,000	10,300	9	Y	9.5	Y
Cyclohexane	1,100,000	1,900	6,300		<1.7	Y
2,2,4-Trimethylpentane	2,400,000	3,540	--		11	Y
Model Results with Biodegradation Included						
Benzene	660,000	3.6	2	Y	3.9	
Toluene	1,100,000	7.18	5,200		33	
Ethylbenzene	150,000	0.795	2		5.7	
Xylenes (total)	150,000	0.22	100		25	
MTBE	5,900,000	4,290	9	Y	9.5	Y
Cyclohexane	1,100,000	0.0884	6,300		<1.7	
2,2,4-Trimethylpentane	2,400,000	162	--		11	Y

Notes: Predicted indoor air concentrations noted as exceeding indoor air criteria (y) or as above background ranges (y). MTBE = methyl tertiary-butyl ether.

Note that BTEX attenuation is three to four orders of magnitude greater with biodegradation included versus neglected. In this scenario, biodegradation significantly contributes to BTEX attenuation. MTBE attenuation is similar (approximately within a factor of 2) with and without biodegradation included. Water-phase aerobic biodegradation rates for MTBE are slow compared to BTEX chemicals. Additionally, 2,2,4-trimethylpentane attenuation is within a factor of 20 with and without biodegradation included. Although the water-phase aerobic biodegradation rate for 2,2,4-trimethylpentane is significant (k_w = 11/hr), the high Henry's Law coefficient and relatively low soil moisture means that this chemical is partitioned predominately into the vapor phase and is therefore not available for biodegradation in the water phase. Cyclohexane attenuation is four orders of magnitude greater with biodegradation included. The moderate Henry's Law coefficient and significant aerobic degradation rate contributes to this estimate.

For this site, follow-up measurements of soil vapor and indoor air were collected and reported for a number of buildings. This included air samples in basements, the first occupied floor, and soil vapor below the building foundation. For a single building (#73), three chemicals were measured above background concentrations in the basement and with sub-foundation to indoor air ratios greater than 10: MTBE, 2,2,4-trimethylpentane, and cyclohexane. The BTEX chemical concentrations measured indoors in all buildings were at or below nominal background levels.

The following equation is used for empirical matching (or checking) of model parameters to measured data across a building foundation, where background contributions can be neglected:

$$\frac{Q_s}{Q_b} = \frac{c_e}{c_f}$$

This indicates the ratio of foundation to building airflow is equal to the building to below-foundation chemical concentration ratio. Values of c_e / c_f calculated from the data, with nominal-estimated building airflow presumed, as in Table H-8, can be used to estimate foundation airflow. Indoor air, c_e, in Table H-19 is the average of basement and ground-floor concentration measurements.

Table H-19. Foundation airflow estimates based on indoor to below-foundation concentration ratios, Case 4—Stafford.

Chemical	Measured Below-Foundation Vapor (µg/m³)	Measured Basement Air (µg/m³)	Measured Ground-Floor Air (µg/m³)	Indoor Air (Median, Literature) (µg/m³)	Indoor to Foundation Ratio, c_e I c_f (--)	Foundation Airflow, Q_s (cm³ (L/min) /sec)	
MTBE	18,000	130	52	6	0.010	103	6.16
2,2,4-Trimethylpentane	96,000	700	160	<5	0.0090	90.9	5.46
Cyclohexane	15,000	130	26		0.010	106	6.33
Average:					0.0098	99.7	5.98

Note: MTBE = methyl tertiary-butyl ether.

This site-specific (building-specific) estimate of Q_s is within the expected range (1 to 10 L/min) for a residential building. It is higher than the initially modeled value by approximately a factor of three. The model has been recalculated with this revised value of Q_s, with Q_s = Q_f, and all other parameters fixed, as in Case B Table H-8. Values entered in BioVapor are shown in Table H-20.

Model results are shown in Table H-21. Note that, while the model comparisons to criteria are similar to the last case, the increased foundation airflow has increased all of the no biodegradation indoor concentration estimates. With biodegradation included, indoor concentrations are decreased for BTEX and cyclohexane due to increased O_2 availability below the building foundation. Estimates of MTBE and 2,2,4-trimethylpentane indoor air concentrations are slightly increased in indoor air.

This completes the analysis for the LNAPL portion of the site. In possible further analysis, an additional analysis can check the sensitivity of indoor air concentration estimates to airflow below the building foundation (Q_f) while holding the foundation airflow through the foundation (Q_s) constant. This modeling simulates the effect of sub-foundation venting without changing the mass transfer characteristics through the foundation.

Table H-20. BioVapor model scenario parameters, Case 4—Stafford; highlighted values are changed from Table H-9.

1. Oxygen Surface Boundary Condition

Slab or Basement Foundation (e.g., Specify Airflow)

2. Indoor Target Criteria

Specified Indoor Air Concentration Target

3. Exposure and Risk Factors

note: not used, as indoor air target criteria are specified

4. Building Parameters

Indoor Mixing Height	L_{mix}	98.41	cm
Air Exchange Rate	ER	11.28	1/day
Foundation Thickness	L_{crack}	10.0	cm
Foundation Area	A_b	790047	cm^2
Foundation Crack Fraction	η	0.00326	cm^2-cracks/cm^2-total
Total Porosity (Soil-filled Cracks)	$\theta_{T\text{-}crack}$	1.00	cm^3-void/cm^3-soil
Water Filled Porosity (Soil-filled cracks)	$\theta_{w\text{-}crack}$	0.00	cm^3-water/cm^3-soil
Airflow Through Basement Foundation	Q_s	99.71	cm^3-air/sec
Building Envelope Resistance	L_{mix} · ER	0.0128	cm/sec

5. Vadose Zone Parameters

Soil Porosity	$\theta_{T\text{-}soil}$	0.378	cm^3-void/cm^3-soil
Soil Water Content	$\theta_{w\text{-}soil}$	0.045	cm^3-water/cm^3-soil
Soil Organic Carbon Fraction	f_{oc}	0.006	(g-oc/g-soil)
Soil Density - Bulk	ρ_s	1.7	(g-soil/cm^3-soil)
Airflow Under Foundation	Q_f	99.71	cm^3-air/sec
Depth of Aerobic Zone Under Foundation	L_s	-	cm
O2 Concentration Under Foundation	$C_{O2\text{-}e}$	-	%
Annual Median Soil Temperature	T	7.5	°C
Baseline Soil Oxygen Respiration Rate		1.2E-07	mg-O_2 / g-sol -sec
Depth to Source (from bottom of foundation)	L_T	165	cm
Minimum O_2 Conc. For Aerobic Biodegradation		1.00	%

Table H-21. Comparison of BioVapor model results to indoor air criteria, Case 4—Stafford.

Chemical	Soil Vapor Source Concentration (µg/m³-air)	Predicted Indoor Air Concentration (µg/m³-air)	Target Indoor Air Concentration (µg/m³-air)		Upper Background Concentration (µg/m³-air)	
Model Results with Biodegradation Neglected						
Benzene	660,000	1,910	2	Y	3.9	Y
Toluene	1,100,000	3,160	5,200		33	Y
Ethylbenzene	150,000	387	2	Y	5.7	Y
Xylenes (total)	150,000	373	100	Y	25	Y
MTBE	5,900,000	15,800	9	Y	9.5	Y
Cyclohexane	1,100,000	2,930	6,300		<1.7	Y
2,2,4-Trimethylpentane	2,400,000	5,050	--		11	Y
Model Results with Biodegradation Included						
Benzene	660,000	0.00295	2		3.9	
Toluene	1,100,000	0.00803	5,200		33	
Ethylbenzene	150,000	6.21E-4	2		5.7	
Xylenes (total)	150,000	1.78E-5	100		25	
MTBE	5,900,000	3140	9	Y	9.5	Y
Cyclohexane	1,100,000	3.21E-8	6,300		<1.7	
2,2,4-Trimethylpentane	2,400,000	7.62	--		11	Y

Notes: Predicted indoor air concentrations are noted as exceeding indoor air criteria (Y) or as above local background ranges (y). MTBE = methyl tertiary-butyl ether.

H.4.5 Case 5—Application to Perth, Western Australia

This example shows use of the BioVapor model to aid the interpretation of site assessment data. The assessment data are published and available (Patterson and Davis 2009). An early version of the BioVapor model V2.0 beta 4, 2 Nov. 2009 (API 2010) was used in the model estimates.

H.4.5.1 Scenario Description

The site scenario is an existing abandoned and unoccupied slab-on-grade building, 18 by 13.5 m (width by length), with a 10-m-wide concrete apron on three sides. The building is located on a petroleum refinery site. The groundwater depth below ground surface is approximately 3.3 m. Kerosene is reported in the capillary smear zone at the water-table depth. Sand soil is present at the site. The site is located approximately 50 km south of Perth, Western Australia.

H.4.5.2 Qualitative Evaluation

Preliminary questions and checks are listed below:

- Is the scenario consistent with conceptual model assumptions?
- Are there other relevant issues that may need to be addressed?

The qualitative criteria for identifying potential issues in VI from subsurface to indoor air, and possible model exceptions, include the following:

- **Is highly affected water or gasoline directly present within or in direct contact with the basement, crawl spaces, sumps, or conduits?** No.
- **Are very large subsurface petroleum NAPL releases near foundations or sub-surface enclosures?** Yes. LNAPL under foundation.
- **Does the site have confined lithology and pressure-driven vapor flow where pressure may originate from rising or falling water tables and/or methane gas generation?** No.

In addition, estimates of O_2 demand (and O_2 presence in the subsurface) are needed:

- O_2 demand in sand soil is low (site measured f_{oc} = 0.0048 g-oc/g-soil)
- Additional O_2 demand originates from PHC vapors evolved from the NAPL or residual petroleum present at water-table depth below the building and adjacent to the building

Criteria for identifying the suspect or confirmed presence of LNAPL are available in ASTM E2531-06 (ASTM International 2006a).

Chemical Vapor Source

Chemical analysis of soil vapor indoors, and at the source, below and adjacent to the building is provided in the cited reference. The source vapor includes specific resolved hydrocarbon chemical components and a significant unresolved PHC fraction. A soil vapor source concentration mixture is included in Table H-22.

Table H-22. Source vapor concentration, Case 5—Perth.

Chemical	Concentration (µg/m^3)	Concentration (g/m^3)
Benzene	<150	<0.00015
Toluene	<150	<0.00015
Ethylbenzene	140,000	0.14
Xylenes (mixed isomers)	<300	<0.0003
Cyclohexane	1,600,000	1.6
Methylcyclohexane	7,300,000	7.30
Unresolved Total Petroleum Hydrocarbons (~C8 aliphatics)	37,959,400	37.95
Total	**47,000,000**	**47**

Nondetects are set at the detection limit in the model estimates. The unresolved hydrocarbons in Table H-22, defined as C8 aliphatics, are reported as dimethylcyclohexanes, branched alkanes and cycloalkanes, and an unresolved mixture of aliphatic hydrocarbons. Qualitative interpretation of the gas chromatography result shows little source vapor contribution greater than approximately C10 in the mixture. The C8 aliphatic fraction in the mixture is a significant fraction of the total mixture and a significant contributor to O_2 demand in this scenario.

Kerosene includes hydrocarbon chemicals of greater molecular weight than C10. These are relatively nonvolatile and would not be quantified in a soil vapor analysis. Groundwater analysis in the vicinity of the building shows detection of ethylbenzene (140 µg/L) and xylenes (220 µg/L). The reported vapor results

and groundwater results are reasonably consistent with expectations for a kerosene-range hydrocarbon source. No methane soil vapor analysis is reported.

Below open ground, adjacent to the building, reported total source vapor concentrations are lower than in Table H-22, totaling approximately 21,000,000 µg/m^3 (21 g/m^3). As volume concentrations, the measured source vapor concentrations below the building and adjacent to the building are, at a 3.3 m depth, approximately:

(47 g/m^3) (0.08206) (293.15) / (100 g/g-mol) = 11.3% v/v [below building]
(21 g/m^3) (0.08206) (293.15) / (100 g/g-mol) = 5.0% v/v [adjacent to building]

The lower flammability limit (LFL) for most fuel hydrocarbons in air (at 21% O_2) is approximately 1% v/v. A flammability screening level in air is often set at 25% of LFL, or nominally, 0.25% v/v.

Source vapor concentration levels are above this 25% of LFL criteria. Note that exceeding this LFL criterion alone does not indicate flammable levels or conditions within the soil matrix because (1) the balance of soil vapor is not air at the subsurface source but is depleted in O_2 and enriched in carbon dioxide and (2) the thermal capacity of the soil matrix will quench flame propagation. It does indicate that flammability may be of potential concern if the vapors could accumulate in a subsurface enclosed space, at and above the flammability criteria limit, in the presence of O_2.

H.4.5.3 Modeling and Analysis

Based on the reference information, the evaluation of VI for conditions reported at this site is presented for three scenarios:

- Scenario 1: Below and within the building.
- Scenario 2: Open ground surface adjacent to the building
- Scenario 3: Below and within the building with the sealed building artificially depressurized by a ventilation fan

Scenario 1: Below and within the building

Several permutations of building ventilation have been documented (Patterson and Davis 2009). This scenario includes variations for which the building was both well sealed and when an open window was simulated. A building depressurization case is described in Scenario 3.

For these scenarios, long-term chemical mass transfer through the building foundation can be estimated through indoor and sub-slab concentration measurements. The advective portion has also been estimated using the time-averaged measured results from a flux chamber placed over a hole drilled through the center of the building foundation (a simulated foundation crack).

From indoor and subsurface measurements of chemical concentrations, and from separate measurement of building air exchange rates, estimates of mass transfer across the building foundation are as follows. For the purpose of data-fitting, advection-dominated chemical mass transfer through a building foundation is:

$$\frac{Q_s}{Q_b} = \frac{c_e}{c_f}$$

Background indoor air contributions can be neglected. Indoor air tracer tests for the fully sealed building and the partly sealed building—open window yielded air ERs of 0.66 and 1.3 /hr, respectively. These

exchange rates and the building volume (760 m^3) yield estimates of building airflow, Q_b. With indoor (c_e) and sub-slab (c_f) concentration measurements of cyclohexane and methylcyclohexane, net airflow through the foundation, Q_s, is estimated as shown in Table H-23.

Table H-23. Estimates of foundation airflow based on indoor to below-foundation concentration ratios, Case 5—Perth.

Chemical	Building	c_e Indoor (mg/m^3)	c_f Sub-Slab (mg/m^3)	Q_s Foundation Airflow (L/min)
Cyclohexane	Fully sealed	.071	800	0.74
Methylcyclohexane	Fully sealed	.29	1,700	1.05
Cyclohexane	Partly sealed	.033	800	0.68
Methylcyclohexane	Partly sealed	.079	1,700	0.57

Estimates can also be made using reported chemical flux into the building (through the flux chamber) and sub-slab concentrations to estimate airflow rates in the range of Q_s = 1 L/min. This value, as shown in Table H-24, is calculated from the reported flux values of 11 and 31 mg/m^2-day for cyclohexane and methylcyclohexane, respectively, multiplied by a foundation area (243 m^2) and divided by the measured sub-slab concentrations of 800 and 1700 mg/m^3.

Table H-24. Estimates of foundation airflow based on foundation flux measurements, Case 5—Perth.

Chemical	Flux (mg/m^2-day)	A_f (m^2)	c_f Sub-Slab (mg/m^3)	Q_s Foundation Airflow (L/min)
Cyclohexane	11	243	800	0.93
Methylcyclohexane	31	243	1,700	1.23

All of the values for Q_s are in reasonable agreement. Some variation may be due to the variable chemical concentrations below the building foundation (from the edge to the center) and due to the chosen location for the drilled foundation hole (the simulated foundation crack). Note this value for Q_s is empirically determined from concentration data. It is a mass transfer coefficient, not an actual or net flow rate of air into the building from the subsurface. Concurrently measured pressure data for the building indicated alternate positive/negative pressure gradients across the building foundation; this confirms two-way advective flow through the foundation.

Nominally, in the modeling, 2.3 L/min (38.3 cm^3/sec) Q_s is chosen as an airflow value through the foundation. Other calculated values for foundation airflow values are in a similar range and yield similar results. Other applied modeling parameters, based on the reference information, are included in Table H-25 and Table H-26. The airflow through the foundation, Q_s, is set equal to the airflow below the foundation, Q_f.

Results are shown in Table H-26. These results indicate reasonable agreement between measured values and modeled values. Both the modeled and measured indoor air concentrations are below nominal chronic indoor air inhalation concentration criteria.

The model results estimate an aerobic depth below the building foundation of 1.35 cm. This minimal value is consistent with the measured and reported absence of O_2 in profiles below the center of the building foundation.

Table H-25. Applied BioVapor model parameters, Case 5—Perth.

Value	Symbol	Parameters
Oxygen Surface Boundary Condition		
		slab or basement foundation (e.g., specify airflow)
Vapor Inhalation Exposure Parameters		
		not applied directly in this case example
Building Parameters and Geometry		
1,800 1,300	W_b L_b	(cm) building width (cm) building length
2,340,000 324.8	$W_b \cdot L_b$ H_b	(cm^2) building footprint area (cm) building height
0 324.8	D_b L_{mix}	(cm) depth to base foundation below grade (cm) enclosed-space volume/infiltration area ratio, or mixing height = Q_b / (A_b·ER)
15.84 760,000,000	ER V_b	(1/day) enclosed-space air exchange rate (cm^3) building volume = $W_b \cdot L_b \cdot H_b$
139,333 8.36	Q_b Q_b	(cm^3/sec) building airflow = $V_b \cdot$ ER (m^3/min) building airflow
2,340,000 19	A_b L_{crack}	(cm^2) subsurface foundation area in contact with soil = W_b·L_b+D_b·2·(W_b+L_b) (cm) enclosed-space foundation or wall thickness
0.0001984	W_{crack}	(cm) crack width - perimeter crack
1.23	A_{crack}	(cm^2) crack area = W_{crack}·2·(W_b+L_b)
5.26E-7 2.298	η Q_s	(cm^2-cracks/ cm^2-total area) foundation crack fraction = A_{crack} / A_b (L/min) soil vapor advection rate
38.3 38.3	Q_s Q_f	(cm^3-air/sec) convective airflow through basement foundation (cm^3-air/sec) convective airflow under basement foundation, Q_f = Q_s or Q_f > Q_s
330 330	L_T	(cm) depth—below basement slab to groundwater depth vapor source (cm) depth—soil surface to groundwater vapor source depth = L_T + D_b
Soil Parameters		
Sand		soil type
0.5 0.11	θ_T θ_w	(cm^3-void/cm^3-soil) soil porosity, vadose-zone soils (cm^3-water/cm^3-soil) soil water content, vadose-zone soils
1 0	θ_T θ_w	(cm^3-void/cm^3-soil) soil porosity, soil-filled basement cracks (cm^3-water/cm^3-soil) soil water content, soil-filled basement cracks
0.0048 1.32	f_{oc} ρ_s	(g-oc/g-soil) soil organic carbon fraction, vadose-zone soils (g-soil/cm^3-soil) soil density—bulk
Environmental Parameters		
20	T_{amb}	(°C) ambient temperature
760	P_{amb}	(mmHg) atmospheric pressure

Key: Specified, derived, and required model parameters are tabulated for Case 1.

Table H-26. BioVapor model results, Case 5—Perth.

Chemical	Sub-Slab Concentration (µg/m³)	Sub-Slab Concentration (µg/m³)	Indoor Air Concentration (µg/m³)	Indoor Air Concentration (µg/m³)
	Measured	Estimated	Measured	Estimated
Benzene	NM	28.9	NM	7.94E-3
Toluene	NM	32.2	NM	8.86E-3
Ethylbenzene	NM	2.96E+4	NM	8.14
Xylene (mixed)	NM	44.9	NM	1.23E-2
Cyclohexane	8.0E+5 ±4.7E+5	1.08E+5	110+/-100	29.7
Methylcyclohexane	2.3E+7 ±1.4E+7	2.47E+6	300 +/- 240	678
C8 Aliphatic	NM	1.5E+7	NM	4,130
Total	4.7E+7 ±1.4E+7	1.76E+7	<50,000	4,840

Note: NM = not measured or reported.

The total estimated sub-slab vapor concentration from the model is:

(17.6 g/m^3) (0.08206) (293.15) / (100 g/g-mol) = 4.2% v/v

Total measured sub-slab concentrations are in the same range:

(47 g/m^3 ± 14 g/m^3) (0.08206) (293.15) / (100 g/g-mol) = 11.3 ± 3.7% v/v

In both the measured data and the modeled results, the sub-slab concentrations are above the nominal criteria for the hydrocarbon flammability limit (25% LFL = 0.25% v/v).

Further, the reference document discusses measured long-term advective flux values of 11 and 31 mg/m^2-day for cyclohexane and methylcyclohexane, respectively, from the created foundation crack. These values include a time-average over which air flows cyclically through the foundation crack, from the subsurface into the building and vice versa. Short-term flux values of up to 4,200 and 12,000 mg/m^2-day, are reported during the period when soil vapor was flowing into the building. These peak flux values in the vicinity of the foundation crack are 380 times the long-term flux mean values. The concentration of soil vapor in the immediate vicinity of a crack is nearly equal to the sub-slab soil vapor concentration. Once mixed into the building, and averaged over time, concentrations are substantially lower.

These results indicate the following:

- Long-term chronic exposure criteria for vapors are met within the building.
- There is the potential for flammable levels of sub-slab soil vapors to flow into the building, immediately adjacent to foundation cracks. Flammability criteria are short term and are best evaluated against short-term concentration estimates or measurements.
- Meeting chronic long-term chemical toxicity criteria is not necessarily protective of potential short-term flammability hazards.

Scenario 1. Notes on vapor diffusion through the concrete slab

Diffusion rates through concrete are documented in measurements for a number of chemicals, including measurements made on a concrete core removed from the building under test in the present example (Table H-27). Most of the measured chemical-specific values fall in a one-order-of-magnitude range of 3.0E-8 to 4.6E-7 m^2/sec, presumably for air-dry concrete. The water-wet concrete diffusion value for O_2 is two orders of magnitude less (4E-10 m^2/sec), which is consistent with expectations, due to reduced air-

filled porosity. As a nominal effective diffusion rate (for dry concrete), an average value from this data has been selected.

Table H-27. Diffusion rates through concrete, Case 5—Perth.

Value	Symbol	Units	Comments
4.6E-7	D_{eff}	(m^2/sec)	Methane. Haghighat, Lee, and Ghaly (2002)
5.1 E-8 to 3.9E-7	D_{eff}	(m^2/sec)	Ethyl acetate. Haghighat, Lee, and Ghaly(2002)
1.0E-7 to 3.0E-7	D_{eff}	(m^2/sec)	N-octane. Haghighat, Lee and, Ghaly (2002)
2.4E-7	D_{eff}	(m^2/sec)	N-dodecane. Haghighat, Lee, and Ghaly (2002)
5.1E-8 to 4.6E-7	D_{eff}	(m^2/sec)	Cyclohexane. Haghighat, Lee, and Ghaly (2002)
3.0E-8 4E-8 (dry) 4E-10 (wet)	D_{eff} D_{eff}	(m^2/sec) (m^2/sec)	Cyclohexane. Patterson and Davis (2009) 0_2. Nominal effective diffusion through air-dry and water-wet concrete (Kobayashi and Shuttoh 1991; Tittarelli 2009) (investigated to attribute steel rebar corrosion rates)
4.3 E-8	D_{eff}	(m^2/sec)	Nominal average effective vapor diffusion rate through dry concrete
2.6E-6	D_{eff}	(m^2/min)	(unit change)

An equivalent advective airflow through the foundation, Q_s, which results in the same mass transfer as a diffusion estimate through the concrete slab, is:

$$Q_s = A_s \cdot \frac{D_{eff}}{L_{slab}}$$

Q_s = (18 m)•(13 m)•(2.6E-6 m^2/min)/(0.19 m) = 0.0032 m^3/min = 3.2 L/min

This calculation indicates that diffusive mass transfer through the concrete foundation is approximately of the same order as empirically estimated using the indoor/sub-slab concentration measurements and the flux measurements in the vicinity of the created crack. In the absence of advection, mass transfer through a foundation is not zero. Diffusive mass transfer through the intact foundation still occurs. Both chemicals and O_2 diffuse through concrete. The diffusive estimate provides a lower limit for minimal mass transfer through an intact foundation and can be re-normalized for larger or smaller foundation areas.

Scenario 1. Notes on chemical-specific vapor attenuation

Table H-28. Chemical-specific concentration ratios, Case 5—Perth.

Chemical	Sub-Slab/Source (measured)	Sub-Slab/Source (estimated)	Indoor Air/Source (measured)	Indoor Air/Source (estimated)
Benzene	NM	>0.19	NM	>5.3E-5
Toluene	NM	>0.22	NM	>5.9E-5
Ethylbenzene	NM	0.21	NM	5.8E-5
Xylenes (mixed)	NM	>0.15	NM	>4.1E-5
Cyclohexane	0.5 ± 0.3	0.068	6.9E-5 ± 6.2E-5	1.9E-5
Methylcyclohexane	3.2 ± 2.0	0.34	4.1E-5 ± 3.3E-5	9.2E-5
C8 Aliphatic	NM	0.4	NM	1.1E-4
Total	1.0 ± 0.3	0.37	<1.0E-3	1.0E-4

Notes: NM indicates a concentration value that is not measured or reported. > indicates the actual value is greater than the value shown (the source concentration in the denominator is below the detection limit). < indicates the actual value is smaller than the value shown (the indoor or sub-slab concentration in the numerator is below the detection limit).

Tabulated sub-slab and indoor vapor concentrations can be divided by the vapor source concentration. Resulting values are shown in Table H-28.

All of the measured sub-slab to source concentration ratios are approximately equal to one; the modeled sub-slab to source values are within an order of magnitude of the measured values. Both the measured and modeled sub-slab to source ratios indicate slightly greater attenuation for cyclohexane than methylcyclohexane. All of the unqualified (no <, >, or NM) indoor air to source concentration ratios are in the 1E-4 to 1E-5 range.

Suggested further evaluation for Case 5:

As further evaluation of this case, running a series of scenarios for varied source concentrations (but the same relative source composition) and tabulating the sub-slab total hydrocarbon vapor concentrations and estimated sub-slab O_2 concentrations would establish an acceptable source concentration below which sub-slab soil vapor would be below flammable criteria limits.

Scenario 2: Open ground surface adjacent to the building

As a permutation, Scenario 2 is run with the BioVapor model with an open ground surface boundary. This is a change of O_2 boundary condition from constant airflow to constant concentration, with 21% O_2 fixed just above the soil surface. This change results in an increase in the calculated aerobic depth from 1.35 cm to 229.4 cm. This result is consistent with site data measurements. Measurable O_2 is monitored at significant concentrations at depth, at the site, in an area where the soil surface is open to the atmosphere and significant vapor concentrations are measured at depth.

Scenario 3: Sealed building artificially depressurized by a ventilation fan

In this evaluation, the sealed building is depressurized by a ventilation fan. In tracer tests, this depressurization increased the building ventilation rate to ER = 2/hr and also resulted in an imposed negative pressure gradient from the soil to indoors of approximately -12 Pa. Monitored indoor concentrations of cyclohexane and methylcyclohexane, respectively, following the depressurization, were reported as 1,100 and 3,400 µg/m^3.

With these increased indoor air concentrations, airflow through the foundation, using

$$\frac{Q_s}{C_e} = \frac{Q_b}{C_f}$$

is estimated to increase to Q_s = 34.8 or 37.4 L/min, with the applicable calculations shown in Table H-29.

Table H-29. Foundation airflow estimates based on indoor to below-foundation concentration ratios for the depressurized building, Case 5—Perth.

Chemical	Building	c_e Indoor (mg/m^3)	c_f Sub-Slab (mg/m^3)	Q_s Foundation Airflow (L/min)
Cyclohexane	Depressurized	1.1	800	34.8
Methylcyclohexane	Depressurized	3.4	1,700	37.4

With the value of Q_s = 34.8 L/min entered in the BioVapor model, a significant aerobic depth below the building foundation is estimated, with an overall decrease (not increase) in indoor air concentrations.

The above discrepancy may have occurred because the model is steady state, and the imposed pressure change on the building and subsurface soil did not continue for a long enough time period for the

transient change in concentrations to approach steady state in the soil layer below the building. There is a discussion of apparent inconsistencies in the flux and concentration measurements in Patterson and Davis (2009).

With increased airflow through the building foundation, additional surface air is drawn under the building, and O_2 levels should increase under the building. The longest time constant, and therefore limiting time period, in this system is in the diffusion-limited transfer of O_2 into soils at depth below the building. A simple estimate of the transient period for O_2 diffusion through soil, neglecting phases other than vapor, and neglecting O_2 consumption, is:

$$\sigma = \sqrt{2 \cdot D_{eff} \cdot t/\theta_a} \text{ or } t = \sigma^2 \frac{\theta_a}{2 \cdot D_{eff}}$$

With σ = 3.3 m (the foundation to source-separation distance), D_{eff} = 0.000149 m^2/min (effective diffusion coefficient for O_2), and the air-filled soil fraction, θ_a- = 0.39 cm^3/cm^3, this yields t = 11,630 minutes (eight days).

Once this approximately eight-day time period has elapsed, the transient change in the soil profile of O_2 and hydrocarbon should reach a new quasi-steady state, and the model is expected to better agree with concentration measurements. The experimental building depressurization test lasted for a period of a few hours, not eight days.

A relevant study of transient O_2 movement below a building foundation has also been reported (Lundegard et al. 2008). The Lundegard data are also consistent with diffusion-limited transfer of O_2 into soils at depth below the building in the time period after the purging of soil vapors below the building with nitrogen and monitoring the return of O_2.

H.4.6 Case 6—Effect of Sealing a Building Foundation for Aerobically Degradable and Nondegradable Chemicals

A possible suggested option for mitigation of VI is better sealing of basement foundations to reduce airflow through the building foundation.

We apply the BioVapor model to qualitatively estimate the effect of a sealed foundation by varying foundation airflow and examining the effect on estimated indoor air concentrations for (1) chemicals that aerobically biodegrade or (2) are recalcitrant to aerobic biodegradation. We estimate the trends using the predicted BioVapor model results that both include and neglect biodegradation.

In this example the BioVapor model scenario is specified with default residential parameters, a source depth of 1 m, and source vapor concentrations including benzene (10 mg/m^3) and labile hydrocarbons (1,000 mg/m^3) for the balance of a hydrocarbon vapor mixture. Results are included in **Figure H-10**, which shows the source to indoor air concentration ratio plotted versus varied airflow through the foundation.

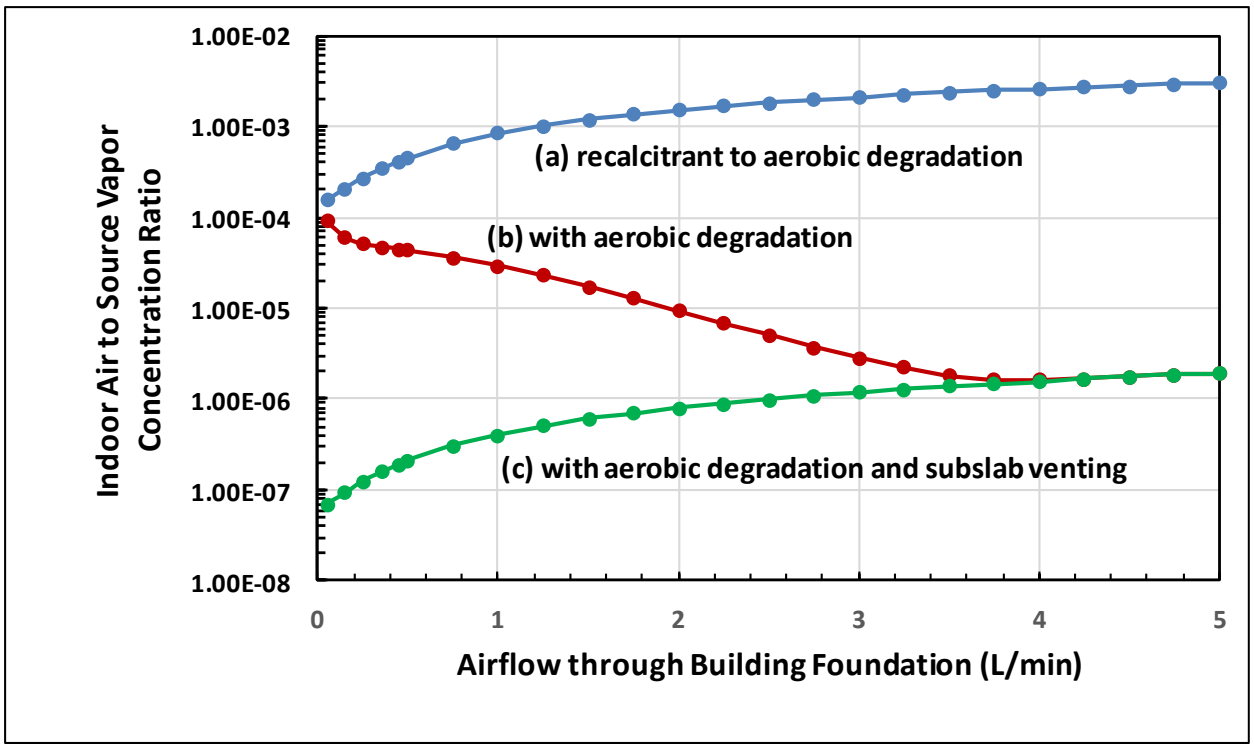


Figure H-10. Estimated indoor to source vapor ratio versus foundation airflow: (a) For a chemical recalcitrant to aerobic degradation a better-sealed foundation reduces indoor air concentrations. (b) For an aerobically degradable chemical a better-sealed foundation may increase indoor air concentrations if oxygen flow into the subsurface (due to the foundation sealing) is reduced. (c) If sub-slab air venting is included (here at a total airflow of 5 L/min) that bypasses the foundation, along with foundation sealing, the estimated trend for aerobic chemicals is reversed.

For chemicals that are recalcitrant to aerobic degradation a better-sealed foundation (lower airflow through the foundation) reduces indoor air concentrations. For aerobically degradable chemicals the opposite trend is observed because a better-sealed foundation also reduces oxygen flow through the foundation into the subsurface. Improved results for degradable chemicals (including hydrocarbons) are possible by including a low level of sub-slab venting (here at a total subsurface airflow of 5 L/min) along with foundation sealing. The sub-slab venting introduces oxygen into the subsurface while bypassing flow though the (sealed) building foundation).

This portion of the page left blank intentionally. The next appendix begins on the following page.

APPENDIX I: JOHNSON AND ETTINGER MODEL INPUTS, OUTPUTS, AND CASE EXAMPLES

This appendix covers four main topics:

- The different compartments for the subsurface to indoor air transport pathway and a coupled model for mass transfer between compartments (excluding biodegradation), which provides valuable insight on the relative attenuation between different compartments
- The Johnson and Ettinger (J&E) model inputs and outputs, and some of the limitations
- Model sensitivities and uncertainties
- Case examples of J&E model applications

I.1 Subsurface to Indoor Air Vapor Pathway and Model Compartments

This section presents a description for subsurface to indoor air vapor migration in terms of coupled model compartments. Each is described briefly below:

- **Indoor building environment:** This area is the indoor occupied living space.
- **Building foundation:** This area of the building is in contact with soil and can include basements, slab-on-grade foundations, or crawl-space foundations.
- **Subsurface environment:** This area includes the soil and groundwater below and adjacent to the building, as well as between the building and the subsurface chemical vapor source.
- **Vapor source:** Vapors may originate from residual nonaqueous-phase liquid (NAPL) or from a downgradient groundwater plume resulting from dissolving NAPL.

Flux between these compartments must be balanced using conservation of mass principles. For example, the indoor air concentration times the air exchange rate in the building rate must equal the rate of mass flux through the floor. If the exchange rate goes up, then the concentration in indoor air will go down.

I.1.1 Indoor Building Environment

The indoor living space occupied by people is defined most simply by an indoor volume V (m^3) and air exchange rate ER (1/day), where ER is the air volume changes in the building per day. Air enters and leaves the enclosure through windows, doors, walls, ceilings, and floors, and by mechanical ventilation. Air exchange varies over time because of weather, operation of the building (mechanical ventilation systems), and building use patterns. The indoor volume is equivalently defined as equal to the building foundation area, A_f, times an effective mixing height, $L_{mix} = V/A_f$. Chemical mass transfer through the building occurs at a rate proportional to ($ER \times L_{mix}$). More complex representations of the indoor environment can include multiple indoor compartments, including varied floors and rooms of a building and air exchange across each of the indoor air spaces.

I.1.2 Building Foundation

The building foundation is the area of the building in contact with soil through which chemicals in the subsurface may migrate to indoor air by either advection or diffusion of soil vapor (or both) through the building foundation. Foundation types include basement, slab-on-grade, and crawl space. Materials of construction for a foundation may vary and can include, for example, bare earth, cobbles, wood, cinder block, and concrete. In addition to materials of construction, air infiltration through a foundation may also be affected by penetrations, such as cracks, underground utilities (water, gas, sewer, and electric), and sumps or drains through which chemicals may preferentially enter a building. Chemicals can enter either through the conduit itself (a sewer line, for example) or through the backfill soils surrounding the conduit. Chemical mass transfer through a building foundation can be defined in terms of either effective airflow, as Q_f /A_f, or effective diffusion, as D_{eff} /L_f, where Q_f is foundation airflow, D_{eff} is the diffusion coefficient through the foundation, A_f is the area of the foundation, and L_f is the thickness of the foundation.

For convenience, vapor transfer through a building foundation is often described in terms of a foundation airflow Q_f for a specified foundation area, A_f, based on measured chemical concentrations in and below the building. This use of Q_f is convenient but may not represent the underlying physical mechanisms, which may be a combination of both diffusion and advection. An average range of approximately Q_f = 1 to 10 L-air/min for a concrete foundation of area A_f = 100 m^2 in contact with the ground is suggested (Hers et al. 2003).

I.1.3 Subsurface Environment—Vadose Zone

The subsurface environment includes the soil and groundwater below and adjacent to the building, as well as between the building and the subsurface chemical vapor source. The subsurface environment may include vadose-zone soils, a capillary fringe, and a water-saturated groundwater zone. The capillary fringe interface separates the vadose zone and groundwater. This description is simplified; subsurface stratigraphy can be complex. Chemical vapor mass transfer through a layer of soil where diffusion dominates is proportionate to D_{eff}/L_T, where D_{eff} is the effective diffusion coefficient through the soil layer and L_T is the thickness of the soil layer. In a layered system, overall diffusion can be estimated from sequential diffusion through each of the layers. The overall rate of diffusion in such systems tends to be controlled by the rate of diffusion through the finest-grained layers because of lower air-filled porosity.

Vapor and gas diffusion rates through a porous soil matrix are significantly higher when the air space in the soil matrix is connected. This connection occurs when the air-filled fraction of soil θ_a(cm^3-air/ cm^3-soil) is greater than approximately 0.2, depending on soil structure. Vapor diffusion is significantly less when the air-filled fraction of soil porosity is disconnected. Disconnection occurs in wetter soils and near the water-table capillary fringe. Soil moisture, θ_w (cm^3-water/ cm^3-soil), which occupies the remaining soil void can therefore significantly affect diffusion in the soil matrix.

I.1.4 Vapor Source

Persistent sources of subsurface vapors in the subsurface originate from residual NAPL resulting from a spill or release to the environment. Vapors may either originate directly from NAPL or from a downgradient groundwater plume resulting from dissolving NAPL. Petroleum hydrocarbons are lighter than water, and light NAPL (LNAPL) from a release is most often trapped at the water-table interface and within the capillary fringe.

Soil vapor concentrations from dissolved groundwater concentrations are typically estimated by an equilibrium partitioning model and the Henry's Law constant. Soil vapor concentrations adjacent to NAPL are estimated with Raoult's law. Partitioning of specific components using Raoult's law is an essential consideration when predicting vapor intrusion (VI) from petroleum LNAPL sources. This consideration is

typically unnecessary when predicting VI at sites with releases of single chemicals, such as sites with chlorinated solvent releases. In both cases measured vapor concentrations may be lower than equilibrium estimates because of diffusion-limited mass transfer either through water-saturated soil zones or through bulk NAPL thickness and biodegradation.

I.1.5 Comparison of Mass Transfer Rates and Relative Attenuation

Migration rates of vapors through buildings, foundations, and soils may be qualitatively compared using mass transfer parameters. Choosing nominal parameter ranges, the mass transfer rates and relative attenuation are calculated as shown in **Table I-1**. The relative attenuation is calculated by simultaneously solving an equation for mass transfer rate for each compartment considered.

Table I-1 Comparison of relative attenuation across compartments.

Compartment	Nominal Parameters	Coefficient	Mass Transfer Rate	Relative Contribution to Attenuation*	Relative Contribution to Attenuation†
Indoors	ER = 12/day, L_{mix} = 2.44 m	$L_{mix} \cdot ER$	29 m/day	1.6E-5	0.001
Foundation	Q_f = 5 L/min, A_f = 100 m2	Q_f / A_f	0.072 m/day	0.007	0.35
Soils—Air Connected	D_{eff} = 0.12 m^2/day, L_T = 3 m	D_{eff} / L_T	0.04 m/day	0.012	0.64
Soils—Wet	D_{eff} = 0.15E-4 m2/day, L_T = 3 cm	D_{eff} / L_T	0.0005 m/day	0.98	--
			Sum:	**1.0**	**1.0**

Notes: A_f = foundation area, D_{eff} = effective diffusion coefficient, ER = exchange rate, L_{mix} = mixing zone height, L_T = layer thickness, Q_f = soil vapor flux into building.
* The apportionment includes the resistance of wet soils in a capillary fringe.
† The apportionment neglects the contribution of capillary fringe resistance.

The table illustrates that, when present, diffusive attenuation across a capillary fringe can be substantial. Attenuation across a typical (concrete) foundation is equivalent to that through several meters of soil. Biodegradation is not included in **Table I-1** but is discussed in a later section.

I.2 Model Inputs/Outputs and Limitations

This section includes a discussion of key input parameters and outputs in the J&E model based on the latest U.S. Environmental Protection Agency (USEPA) and California Environmental Protection Agency (CalEPA) Department of Toxic Substances Control (DTSC) implementation in an Excel Workbook. Detailed technical information and model instructions can be found in the Documentation for USEPA's Implementation of the J&E model (USEPA 2017b) and User's Guide for DTSC Implementation of the J&E model (California DTSC 2024). The screenshots shown in this section are based on the California DTSC-modified version and may be different from those in the USEPA spreadsheet.

I.2.1 Model Inputs

The following worksheets contain key model inputs and data entry:

MODEL: Enter key model input values based on the site VI conceptual site model (CSM).

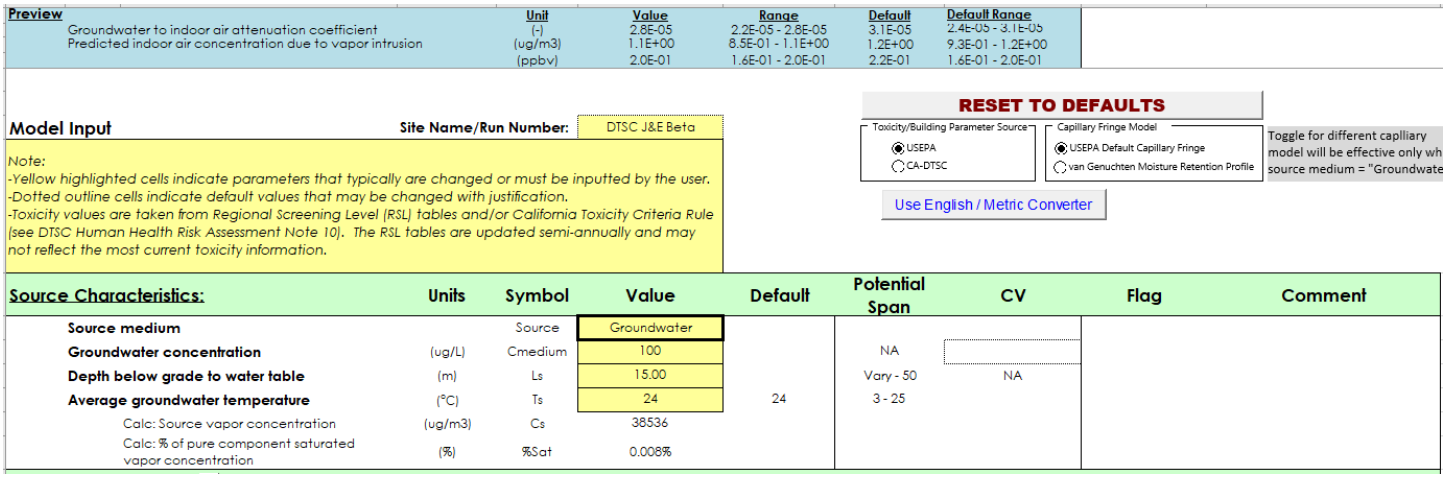
MULTI_CHEM_INPUT: Soil vapor or groundwater concentrations for all chemicals of potential concern for a site may be entered here to evaluate the VI pathway for multiple chemicals within a single workbook.

MEASURED_SOIL_GAS_CONC: Entry of depth-dependent contaminant concentrations in soil vapor for comparison with the modeled concentration profile.

The VI CSM and modeling objectives should be reviewed to identify required input values to use the J&E model. The necessary input cells are highlighted in yellow on this worksheet. Sufficient justification is needed for changes from default values for unhighlighted input cells.

The input categories include source characteristics, chemical properties, building characteristics, vadose-zone characteristics, and exposure parameters.

Source characteristics include source medium (i.e., groundwater, exterior soil vapor, or sub-slab soil vapor), source concentration, source depth, and groundwater/vadose-zone temperature.



Preview		Unit	Value	Range	Default	Default Range
	Groundwater to indoor air attenuation coefficient	(-)	2.8E-05	2.2E-05 - 2.8E-05	3.1E-05	2.4E-05 - 3.1E-05
	Predicted indoor air concentration due to vapor intrusion	(ug/m3)	1.1E+00	8.5E-01 - 1.1E+00	1.2E+00	9.3E-01 - 1.2E+00
		(ppbv)	2.0E-01	1.6E-01 - 2.0E-01	2.2E-01	1.6E-01 - 2.0E-01

Model Input — Site Name/Run Number: DTSC J&E Beta

RESET TO DEFAULTS

Toxicity/Building Parameter Source: USEPA / CA-DTSC

Capillary Fringe Model: USEPA Default Capillary Fringe / van Genuchten Moisture Retention Profile

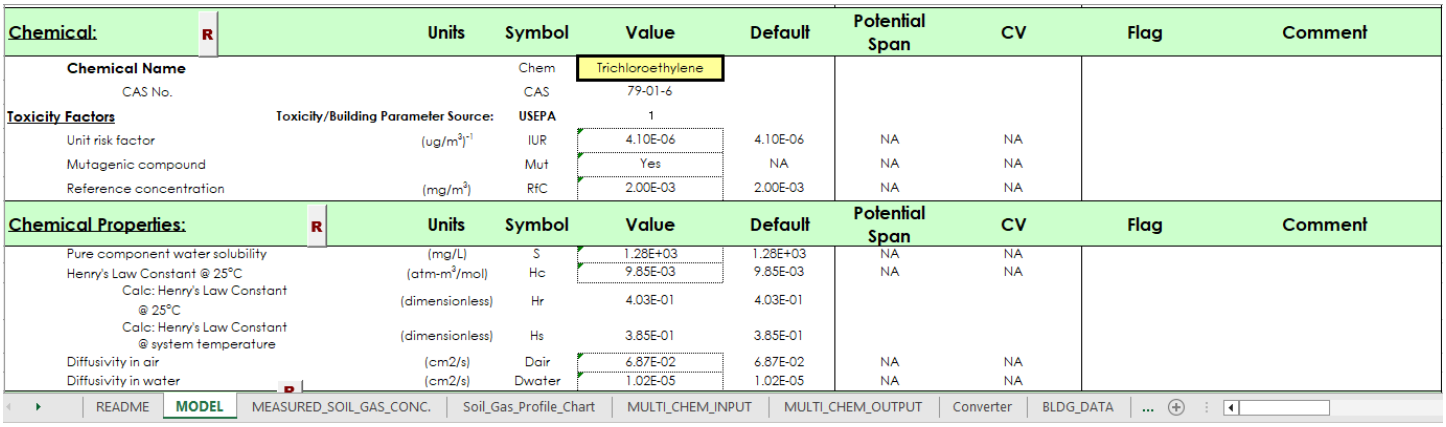
Toggle for different capillary model will be effective only wh source medium = "Groundwate

Use English / Metric Converter

Note:
-Yellow highlighted cells indicate parameters that typically are changed or must be inputted by the user.
-Dotted outline cells indicate default values that may be changed with justification.
-Toxicity values are taken from Regional Screening Level (RSL) tables and/or California Toxicity Criteria Rule (see DTSC Human Health Risk Assessment Note 10). The RSL tables are updated semi-annually and may not reflect the most current toxicity information.

Source Characteristics:	Units	Symbol	Value	Default	Potential Span	CV	Flag	Comment
Source medium		Source	Groundwater					
Groundwater concentration	(ug/L)	Cmedium	100		NA			
Depth below grade to water table	(m)	Ls	15.00		Vary - 50	NA		
Average groundwater temperature	(°C)	Ts	24	24	3 - 25			
Calc: Source vapor concentration	(ug/m3)	Cs	38536					
Calc: % of pure component saturated vapor concentration	(%)	%Sat	0.008%					

Chemical properties include chemical and physical parameters and toxicity factors. Once the chemical name is entered, the J&E model spreadsheet looks up the appropriate chemical properties from reference tables and populates this information into the MODEL worksheet.



Chemical: R	Units	Symbol	Value	Default	Potential Span	CV	Flag	Comment
Chemical Name		Chem	Trichloroethylene					
CAS No.		CAS	79-01-6					
Toxicity Factors — Toxicity/Building Parameter Source:		USEPA	1					
Unit risk factor	$(ug/m^3)^{-1}$	IUR	4.10E-06	4.10E-06	NA	NA		
Mutagenic compound		Mut	Yes	NA	NA	NA		
Reference concentration	(mg/m^3)	RfC	2.00E-03	2.00E-03	NA	NA		

Chemical Properties: R	Units	Symbol	Value	Default	Potential Span	CV	Flag	Comment
Pure component water solubility	(mg/L)	S	1.28E+03	1.28E+03	NA	NA		
Henry's Law Constant @ 25°C	$(atm\text{-}m^3/mol)$	Hc	9.85E-03	9.85E-03	NA	NA		
Calc: Henry's Law Constant @ 25°C	(dimensionless)	Hr	4.03E-01	4.03E-01				
Calc: Henry's Law Constant @ system temperature	(dimensionless)	Hs	3.85E-01	3.85E-01				
Diffusivity in air	(cm2/s)	Dair	6.87E-02	6.87E-02	NA	NA		
Diffusivity in water	(cm2/s)	Dwater	1.02E-05	1.02E-05	NA	NA		

README | MODEL | MEASURED_SOIL_GAS_CONC. | Soil_Gas_Profile_Chart | MULTI_CHEM_INPUT | MULTI_CHEM_OUTPUT | Converter | BLDG_DATA

Building characteristics are typically defined by selecting the building setting (i.e., residential or commercial) and foundation type (slab-on-grade, basement, or crawl-space construction) from the drop-down menu. Site-specific building factors can be used with justification.

Building Characteristics:

Select Building Assumptions

(•) Use ratio for Qsoil/Qbuilding (recommended if no site specific data available)

( ) Specify Qsoil and Qbuilding separately; calculate ratio

Click to change assumptions

	Units	Symbol	Value	Default	Potential Span	CV	Flag	Comment
Building setting		Bldg_Setting	Residential	Residential				
Foundation type		Found_Type	Slab-on-grade	Slab-on-grade				
Depth below grade to base of foundation	(m)	Lb	0.10	0.10	0.1 - 2.44	NA		
Foundation thickness	(m)	Lf	0.10	0.10	0.1 - 0.25	NA		
Fraction of foundation area with cracks	(-)	eta	0.001	0.001	0.00019-0.0019	1.00		
Enclosed space floor area	(m2)	Abf	150.00	150.00	80 - 200	NA		
Enclosed space mixing height	(m)	Hb	2.44	2.44	2.13 - 3.05	NA		
Indoor air exchange rate	(1 / hr)	ach	0.45	0.45	0.15-1.26	NA		
Qsoil/Qbuilding	(-)	Qsoil_Qb	0.0030	0.0030	0.0001 - 0.05	1.24		
Calc: Building ventilation rate	(m3/hr)	Qb	164.70	164.70	NA	0.30		
Calc: Average vapor flow rate into building	(m3/hr)	Qsoil	0.49	0.49	NA	NA		

Vadose-zone characteristics include classifications of up to three soil layers from the 12 USDA Soil Conservation Service soil texture classes. The sum of the thicknesses for the different strata must equal the source depth entered in the Source Characteristic section of the inputs. If stratum B or C is not needed for the model input, the soil type input cells for these strata should be blank, and the stratum thickness should be set to zero. The J&E model spreadsheet automatically enters default soil properties from the lookup table. Site-specific soil properties may be entered if sufficient data are available.

Vadose zone characteristics: R	Units	Symbol	Value	Default	Potential Span	CV	Flag
Stratum A (Top of soil profile):							
Stratum A SCS soil type		SCS_A	Sand				
Stratum A thickness (from surface)	(m)	hSA	5.00				
Stratum A total porosity	(-)	nSA	0.375	0.375	NA	0.20	
Stratum A water-filled porosity	(-)	nwSA	0.054	0.054	0.053 - 0.055	0.25	
Stratum A bulk density	(g/cm^3)	rhoSA	1.660	1.660	NA	0.05	
Stratum B (Soil layer below Stratum A):							
Stratum B SCS soil type		SCS_B	Clay Loam				
Stratum B thickness	(m)	hSB	5.00				
Stratum B total porosity	(-)	nSB	0.442	0.442	NA	0.20	
Stratum B water-filled porosity	(-)	nwSB	0.168	0.168	0.079 - 0.26	0.25	
Stratum B bulk density	(g/cm^3)	rhoSB	1.480	1.480	NA	0.05	
Stratum C (Soil layer below Stratum B):							
Stratum C SCS soil type		SCS_C	Sandy Clay Loam				
Stratum C thickness	(m)	hSC	5.00				
Stratum C total porosity	(-)	nSC	0.384	0.384	NA	0.20	
Stratum C water-filled porosity	(-)	nwSC	0.146	0.146	0.063 - 0.23	0.25	
Stratum C bulk density	(g/cm^3)	rhoSC	1.630	1.630	NA	0.05	
Stratum containing soil gas sample							
Stratum A, B, or C		src_soil	Stratum C				
					NA	NA	
					NA		

README | MODEL | MEASURED_SOIL_GAS_CONC. | Soil_Gas_Profile_Chart | MULTI_CHEM_INPUT | MULTI_CHEM_OUTPUT | Converter | BLDG_DATA | ...

Exposure parameters are used for risk calculations and are populated based on the building setting (i.e., residential, or commercial). The target risk and target hazard can be input for calculation of risk-based target screening levels.

Exposure Parameters: R	Units	Symbol	Value	Default	Potential Span	CV	Flag
Target risk for carcinogens	(-)	Target_CR	1.00E-06	1.00E-06	NA	NA	
Target hazard quotient for non-carcinogens	(-)	Target_HQ	1	1	NA	NA	
Exposure Scenario		Scenario	Residential	Residential			
Averaging time for carcinogens	(yrs)	ATc	70	70	NA	NA	
Averaging time for non-carcinogens	(yrs)	ATnc	26	26	NA	NA	
Exposure duration	(yrs)	ED	26	26	NA	NA	
Exposure frequency	(days/yr)	EF	350	350	NA	NA	
Exposure time	(hrs/24 hrs)	ET	24	24	NA	NA	
Mutagenic mode-of-action factor	(yrs)	MMOAF	72	72	NA	NA	

README | MODEL | MEASURED_SOIL_GAS_CONC. | Soil_Gas_Profile_Chart | MULTI_CHEM_INPUT | MULTI_CHEM_OUTPUT | Converter | BLDG_DATA | ...

I.2.2 Model Outputs/Reporting

Model outputs are primarily displayed in the following worksheets:

MODEL worksheet: J&E model output for chemicals included in the MODEL worksheet is shown in two different sections. The first section of Model Output includes attenuation factors (AFs), predicted indoor air concentration, predicted sub-slab vapor concentration, effective diffusion coefficients, critical parameters controlling vapor transport through soil and across the building foundation, and a plot to compare the modeled soil vapor concentration profile with measured data by depth that the user has the option to enter on the MEASURED_SOIL_GAS_CONC. worksheet.

Model Output Site Name/Run Number: DTSC J&E Case

Chemical Name: Trichloroethylene CAS No. 79-01-6

Range is based on the reasonable range of Qsoil/Qbuilding values, as reported in the literature.

Source to Indoor Air Attenuation Factor	Units	Symbol	Value	Range	Default	Default Range	Flag
Groundwater to indoor air attenuation coefficient	(-)	alpha	3.7E-04	8.5E-05 - 4.1E-04	3.7E-04	8.5E-05 - 4.1E-04	

Predicted Indoor Air Concentration	Units	Symbol	Value	Range	Default	Default Range	Flag
Indoor air concentration due to vapor intrusion	(ug/m3)	Cia	1.2E-01	2.7E-02 - 1.3E-01	1.2E-01	2.7E-02 - 1.3E-01	
	(ppbv)		2.2E-02	5.1E-03 - 2.5E-02	2.2E-02	5.1E-03 - 2.5E-02	

Predicted Vapor Conc. Beneath Foundation	Units	Symbol	Value	Range	Default	Default Range	Flag
Subslab vapor concentration	(ug/m3)	Css	3.9E+01	2.7E+00 - 2.7E+02	3.9E+01	2.7E+02 - 1.3E+03	
	(ppbv)		7.3E+00	4.9E-01 - 5.1E+01	7.3E+00	5.1E+01 - 2.5E+02	

Diffusive Transport Upward Through Vadose Zone	Units	Symbol	Value	Range	Default	Default Range	Flag
Effective diffusion coefficient through Stratum A	(cm2/sec)	DeffA	1.1E-02	-	1.1E-02	-	
Effective diffusion coefficient through Stratum B	(cm2/sec)	DeffB		-		-	
Effective diffusion coefficient through Stratum C	(cm2/sec)	DeffC		-		-	
Effective diffusion coefficient through capillary zone	(cm2/sec)	DeffCZ	4.4E-04	-	4.4E-04	-	
Effective diffusion coefficient through unsaturated zone	(cm2/sec)	DeffT	6.0E-03	-	6.0E-03	-	

Critical Parameters		Symbol	Value	Range	Default	Default Range	Flag
α for diffusive transport from source to building with dirt floor foundation	(-)	A_Param	4.2E-04	-	4.2E-04		
Pe (Peclet Number) for transport through the foundation (advection / diffusion)	(-)	B_Param	8.0E+01	2.7E+00 - 1.3E+03	8.0E+01	2.7E+00 - 1.3E+03	
α for convective transport from subslab to building	(-)	C_Param	3.0E-03	1.0E-04 - 5.0E-02	3.0E-03	1.0E-04 - 5.0E-02	

Interpretation

Advection is the dominant mechanism across the foundation.
Diffusion through soil and advection through foundation both control intrusion.

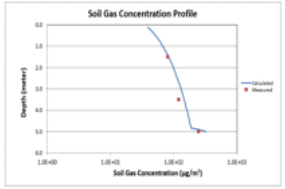
Critical Parameters

Hb, Ls, DeffT, ach, Qsoil_Qb

Non-Critical Parameters

Lf, DeffA, eta

The Soil Gas Profile Plot has been moved to "MEASURED_SOIL_GAS_CONC." tab for side-by-side comparison.



The second section of Model Output includes the risk calculations of cancer risk and noncancer hazard estimates (forward calculations) as well as the risk-based target screening levels or cleanup goals (inverse or backward calculations).

Model Output Site Name/Run Number: Example Run 1
Chemical Name: Trichloroethylene CAS No. 79-01-6

Risk Calculations	Units	Symbol	Value	Range	Default	Range
Risk-Based Target Screening Levels	Scenario: Commercial					
Target risk for carcinogens	(-)	Target_CR	1E-06	-	1E-06	-
Target hazard quotient for noncarcinogens	(-)	Target_HQ	1	-	1	-
Target indoor air concentration	**(ug/m3)**	**Target_IA**	**2.05E+00**	-	**2.05E+00**	-
Target soil gas concentration	**(ppbv) (ug/m3)**	**Target_SV**	**3.82E-01 1.12E+04**	- **1.1E+04 - 3.1E+04**	**3.82E-01 1.12E+04**	- **1.1E+04 - 3.1E+04**
Incremental Risk Estimates						
Incremental cancer risk from vapor intrusion	**(-)**	**Cancer_Risk**	**2.62E-06**	**9.4E-07 - 2.8E-06**	**2.62E-06**	**9.4E-07 - 2.8E-06**
Hazard quotient from vapor intrusion	**(-)**	**HQ**	**2.30E-01**	**8.3E-02 - 2.4E-01**	**2.30E-01**	**8.3E-02 - 2.4E-01**

The MULTI_CHEM_OUTPUT worksheet displays the J&E model output for multiple chemicals selected in the MULTI_CHEM_INPUT worksheet (an example of input concentrations for four contaminants is shown below).

Input Chemical Concentrations for Multiple Chemicals

*Note: All other inputs **must** be entered in model sheet. For multi-chemical mode, **all inputs except concentration must be the same for all chemicals**. Model calculations will be completed and added to MULTI_CHEM_OUTPUT sheet for those chemicals with a concentration entered.*

Calculate

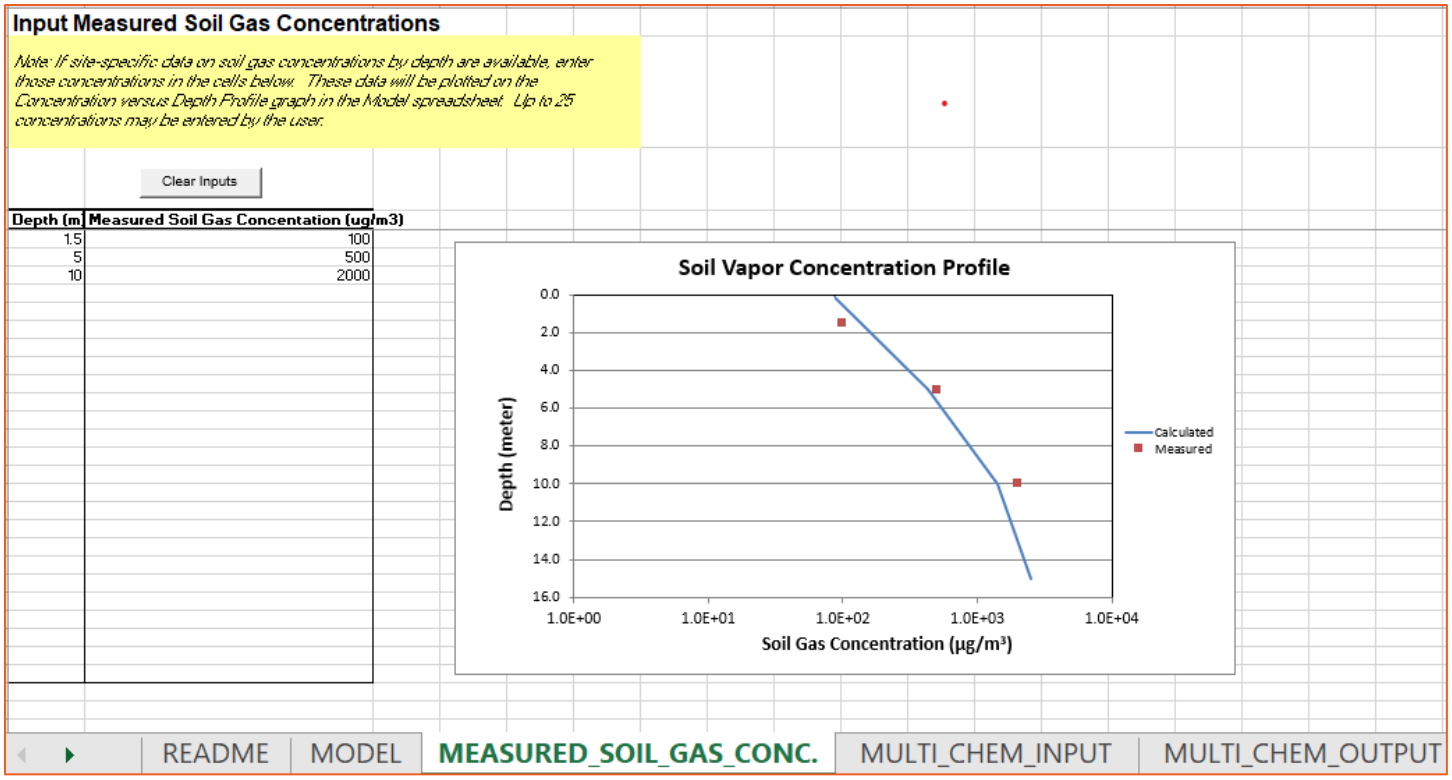
Clear Inputs

USEPA toxicity values used

Chemical List	CASRN	Concentration (µg/L) or (µg/m3)
Benzene	71-43-2	1
Chloroform	67-66-3	
Dichloroethane, 1,2-	107-06-2	
Dichloroethylene, 1,1-	75-35-4	
Dichloroethylene, 1,2-cis-	156-59-2	
Dichloroethylene, 1,2-trans-	156-60-5	
Ethylbenzene	100-41-4	
Hexane, N-	110-54-3	
Naphthalene	91-20-3	
Tetrachloroethane, 1,1,2,2-	79-34-5	
Tetrachloroethylene	127-18-4	1
Toluene	108-88-3	
Trichloroethane, 1,1,1-	71-55-6	
Trichloroethylene	79-01-6	1
Vinyl Chloride	75-01-4	1
Xylenes	1330-20-7	

README | MODEL | MEASURED_SOIL_GAS_CONC. | Soil_Gas_Profile_Chart | MULTI_CHEM_INPUT | MULTI_CHEM_OUTPUT | Converter

The MEASURED_SOIL_GAS_CONC. worksheet provide the option to enter measured soil vapor data to display in the soil vapor concentration profile plot for comparison with modeled soil vapor concentration profile.



When reporting modeling results, the following items are recommended to facilitate review:

- Tables listing all model input parameters and values and technical justifications for those that deviated from the default values; the parameters should be presented using the same units as are shown in the model
- Copies of key Excel worksheets showing inputs and results in the MODEL and MULTI_CHEM_INPUT worksheets as well as the MULTI_CHEM_OUTPUT worksheet (if multiple chemicals are selected)
- A summary of risk calculations along with the verification (where applicable; see below) and uncertainty analysis including tables comparing the ranges of the variables under study and corresponding model predictions
- Where available, empirical data should also be provided for a side-by-side comparison by presenting the soil vapor profile plot in the MEASURED_SOIL_GAS_CONC. worksheet

I.2.3 Model Limitations

A detailed discussion of all relevant assumptions and the corresponding implications and field interpretation is presented in Table 4 of the USEPA User's Guide (USEPA 2017b). Based on these assumptions and implications, the following conditions may preclude or limit the use of the model:

- The presence or suspected presence of residual or free-product NAPL (LNAPL, dense NAPL, fuels, solvents, etc.) in the subsurface

- The presence of heterogeneous geologic materials (other than the three layers allowed in the advanced spreadsheets) between the vapor source and building
- Sites where significant lateral flow of vapors occurs, including geologic layers that deflect contaminants from a strictly upward motion and buried pipelines and other conduits or openings that form preferential paths
- Very shallow groundwater where the building foundation is wetted by the groundwater (the model assumes that the capillary fringe is not contaminated)
- Very small building air exchange rates (e.g., < 0.25/h)
- Contaminated groundwater sites with large fluctuations in the water-table elevation

The J&E model does not account for the bioattenuation of degradable compounds (e.g., many petroleum hydrocarbons), and biodegradation models such as BioVapor (**Appendix H**) may be used in those cases. Other site-specific conditions should also be considered as they may limit the applications of the J&E model. For example, paving and construction of buildings can reduce vapor emissions from soil, causing a capping effect and limiting infiltration of water, potentially resulting in lower soil moisture content and enhanced and/or altered vapor migration. Three-dimensional VI modeling suggests that the vertical distribution of vapor-forming chemicals (VFCs) in shallow soil vapor can be affected by a building slab, potentially leading to lower exterior shallow soil vapor concentrations relative to levels beneath the building by factors of approximately two to five (USEPA 2012a). Site development can also introduce human sources of moisture in the subsurface including irrigation or, as the site ages, water from broken sewer pipes and water supply lines that can reduce and/or alter vapor migration.

If the VI CSM is not consistent with model assumptions, the uncertainties and potential impact of site conditions should be considered when interpreting the modeled estimates, and a discussion of the potential impact of these differences should be included with the model evaluation.

I.3 Model Sensitivities and Uncertainties

The sensitivity of the J&E model outputs to key input parameters is qualitatively described in **Table I-2** below:

Table I-2: Effect of an increase in input parameter values on in-building concentration.

Input Parameter Increased	Effect on Building Concentration
Media Initial Concentration (C_{medium})[a]	Increase
Depth Below Grade to Base of Foundation (L_b)	Increase
Indoor Air Exchange Rate (ach)	Decrease
Building Volume[b] ($L_b \times A_b$)	Decrease
Soil Total Porosity (nSX)[c]	Increase
Soil Dry Bulk Density (rhoSX) [c]	Decrease

Notes: a. This parameter is applicable only when forward-calculating risk.
b. Used with building air exchange rate to calculate building ventilation rate.
c. Where X=stratum A, B, or C.

Source: Adapted from USEPA (2017b).

Other input parameters are generally less sensitive and/or difficult to estimate (e.g., crack ratio, pressure differential, and associated Q_{soil} term) on a site-specific basis, and default or protective values are

recommended for these parameters to reduce uncertainty in model predictions. Additional discussion of the uncertainties regarding the J&E model can be found in Hers et al. (2003) and Weaver and Tillman (2005).

The USEPA J&E spreadsheet also presents three critical parameter groups proposed by (2005) to help evaluate the various transport processes for VI and related model inputs:

- A_{param} represents the ratio of the diffusive flow rate in soil and the building ventilation rate, that is, the AF for diffusive transport from the source to a building with a dirt floor foundation.
- B_{param} represents the equivalent Peclet number, that is, the ratio of advective flow rate and diffusive flow rate for transport through the building foundation and can indicate whether advection or diffusion is the dominant mechanism of transport across the foundation.
- C_{param} represents the ratio of the vapor flow rate into a building and the building ventilation rate (Q_{soil} / Q_b), that is, the AF for convective transport from sub-slab to building.

These parameter groups are interpreted to determine the rate-limiting transport process or processes that control VI for a given site condition or model scenario. This information can be useful to identify critical model inputs for sensitivity analysis and/or additional data collection.

I.4 Case Examples

I.4.1 Comparison of Modeled and Empirical Attenuation Factors

In this case example, the AFs estimated by the J&E model were compared with the empirical AFs calculated using measured soil vapor and indoor air concentrations at an existing building.

I.4.1.1 Site Data Description/Methodology

The site comprises approximately 26 acres with five buildings and is in an area of commercial/industrial operations. It was formerly operated by an aircraft company for component design, testing, and assembly. Currently, the buildings are leased to tenants for various office and storage uses.

Environmental investigations were conducted to support cleanup and closure of several waste management units on-site. Specifically, the potential exists for VFCs to volatilize from the subsurface into indoor air at the on-site buildings. Soil matrix, soil vapor, and indoor air samples were collected around the building located near the two former solvent tanks for tetrachloroethene (PCE) and trichloroethylene or trichloroethene (TCE). The data were evaluated in a human health-risk assessment (HHRA) for potential VI and other exposure pathways.

I.4.1.2 Modeling Discussion

The VI pathway was evaluated using the J&E model to estimate potential migration of subsurface vapors into indoor air at the on-site buildings. For this HHRA, soil vapor risk-based concentrations were derived using the J&E model and based on various sampling depths of 0.5 feet (i.e., sub-slab at 5-, 10-, 15-, and 25-feet below ground surface [bgs]). The geometric mean of the site-specific soil physical parameters (bulk density, total soil porosity, and water-filled porosity) for three different zones (A = 0–5 feet bgs; B = >5–10 feet bgs; and C = >10–20 feet bgs) used in the model are summarized in **Table I-3**.

Table I-3. Summary of soil physical properties.

Soil Stratum	Bulk Density (kg/L)	Total Porosity (%)	Moisture Content (% wt)	Estimated Water-Filled Porosity (%)
A (0–5 feet bgs)	1.49	37.6	19.3	28.9
B (>5–10 feet bgs)	1.55	34.7	10.6	16.5
C (>10–20 feet bgs)	1.51	40.5	16.7	25.3

Note: bgs = below ground surface.

The J&E VI model also requires the characterization of several building-specific parameters including building size (area and floor height), slab thickness, ventilation rate, and volumetric flow rate of soil vapor into the building. Table I-4 lists the default and site-specific model input parameters used for Building A.

Table I-4. Input parameters for Building A.

Model Input Parameter	Value Used	Rationale
Soil Properties		
Average soil/groundwater temperature (Ts), °C	19	Area-specific average
Depth below grade to bottom of enclosed space floor (L_F), cm	15	Slab construction
Soil gas sampling depth below grade (L_S), cm	--	Depth at which samples were collected
Thickness of soil stratum A h_A), cm	L_s	Depth-to-soil gas sample
Soil stratum A SCS soil typ	SIC	Silty clays soil type
Stratum A soil dry bulk density, gm/cm^3	1.49	Site-specific geomean value based on soil physical property testing
Stratum A soil total porosity, unitless	0.376	Site-specific geomean value based on soil physical property testing
Stratum A soil water-filled porosity, cm^3/cm^3	0.289	Site-specific geomean value based on soil physical property testing
Stratum B soil dry bulk density, gm/cm^3	1.55	Site-specific geomean value based on soil physical property testing
Stratum B soil total porosity, unitless	0.347	Site-specific geomean value based on soil physical property testing
Stratum B soil water-filled porosity, cm^3/cm^3	0.165	Site-specific geomean value based on soil physical property testing
Stratum C soil dry bulk density, gm/cm^3	1.51	Site-specific geomean value based on soil physical property testing
Stratum C soil total porosity, unitless	0.405	Site-specific geomean value based on soil physical property testing
Stratum C soil water-filled porosity, cm^3/cm^3	0.253	Site-specific geomean value based on soil physical property testing
Crack-to-total-area ration (η), unitless	0.005	Default assumption
Commercial Building Parameters		
Enclosed space floor thickness (L_{crack}), cm	10	Default assumption
Enclosed space floor length (L_B), cm	1,000	Default assumption (10 m)
Enclosed space floor width (W_B), cm	1,000	Default assumption (10 m)
Enclosed space height (H_B), cm	366	Proposed ceiling height (12 feet or 3.66 m)
Floor-wall seam crack width (w), cm	0.1	Default assumption
Indoor air exchange rate (ER), 1 per hour	1	Default commercial building assumption
Average vapor flow rate into building (Q_{soil}) L/m	5	Based on 5 L/m per 100 m^2 of building floor space

Note: The latest USEPA spreadsheet (2017d) uses the ratio of Q_{soil} and building ventilation rate (Q_b) as a single variable in the default mode (see the discussion below).

I.4.1.3 Comparison of Attenuation Factors

Both soil vapor and indoor air concentrations have been measured previously at this site. No indoor sources of PCE or TCE were identified during the building survey prior to the indoor air sampling. Consequently, an empirical AF (i.e., the ratio of the measured paired indoor air and soil vapor concentrations) may be calculated and compared to the AFs estimated for PCE and TCE by the J&E model as shown in Table I-5.

Table I-5. Comparison of modeled and measured attenuation factors.

Sample Depth	Sub-Slab	5 feet bgs	15 feet bgs
Modeled AF	7E-4	1E-5	9E-6
Empirical AF—Maximum	5E-5	7E-6	3E-6
Empirical AF—Average	2E-5	5E-6	1E-6

Note: bgs = below ground surface.

I.4.1.4 Summary and Lessons Learned

1. The modeled sub-slab AF is an order of magnitude higher than the empirical AFs based on the measured data. Thus, using the modeled AF for sub-slab samples will predict higher indoor air concentrations than the measured data show.
2. The modeled AFs for the 5-ft and 15-ft bgs sample depths are also approximately a factor of two to three times higher than the maximum AFs based on the measured data. This suggests the VI modeling using site-specific soil properties is conservative and overestimates the potential VI risk for soil vapor.
3. The indoor air measurements used in the empirical AF calculations were taken when the heating, ventilation, and air conditioning system was operating in the building and the pressure differential measurements across the foundation confirmed a positive pressure within the building for the sampling duration. The model did not account for these building conditions, which likely minimized vapor migration from the subsurface into indoor air, and it may be one reason why the empirical AFs were lower than the model-predicted AFs.
4. The use of Q_{soil} and building ventilation rate (Q_b) as separate model inputs in this case resulted in a Q_{soil}/Q_b ratio of 0.0008, which is significantly lower than the default values in the latest USEPA and California DTSC spreadsheets (0.003 and 0.03, respectively). Changing the Q_{soil}/Q_b ratio has a negligible effect on the estimated AF for 5-ft and 15-ft bgs sample depths as the vapor transport is limited by the diffusion in soil in this case.
5. It is important to perform a sensitivity analysis on key model input parameters and to compare modeling results with empirical data, when possible, to verify that the modeling provides representative or conservative estimates of indoor air exposures. The above comparison between modeled and empirical AFs was based on a single sampling event, and additional rounds of sampling data are desirable for assessing possible temporal variations and providing higher confidence in the model predictions.

I.4.2 Development of Depth-Specific Cleanup Goals for Soil Vapor

In this case example, the J&E model was used as a line of evidence to develop depth-specific cleanup goals for soil vapor by comparing model-predicted AFs with empirical values based on measured soil vapor concentrations at different depths.

I.4.2.1 Site Data Description/Methodology

The site comprises approximately 6 acres and is located in an area of mixed commercial, light industrial, and residential uses. It is currently vacant with no surface cover and surrounded by fencing. It is proposed for development into multiple residential units including townhomes and duplexes as well as retail space. The former operations included machine shops, trucking and shipping companies, and automotive supply/repair facilities.

Previous environmental investigations conducted at the site found PCE in soil and soil vapor in several areas. Groundwater is approximately 80 feet bgs at the site, and PCE was detected in on-site and upgradient off-site groundwater monitoring wells, indicating regional groundwater impacts. A remedial action plan was prepared to propose a soil vapor extraction (SVE) system targeting the vadose zone above the fine-grain unit (starting at approximately 30 feet bgs) in the on-site source areas. Preliminary remediation goals were developed to address potential VI for PCE in soil vapor for the shallow (5–12 feet bgs) and intermediate (20–30 feet bgs) zones.

I.4.2.2 Modeling Discussion

Inputs to the J&E model for the calculation of soil vapor-to-indoor air AFs include soil properties, building parameters, and depth of soil vapor contamination. Chemical- and depth-specific AFs were calculated for a hypothetical future on-site residential building. Based on the lithologic information from boring logs, vadose-zone soil properties were set to USEPA default values for the loamy sand soil type. Default building size assumptions for hypothetical single-residence units were used. The soil and building parameters used in the J&E model are summarized in Table I-6.

Table I-6. Summary of model input parameters.

Parameter	Symbol	Residential	Units	Rationale
Building Properties				
Depth Below Grade to Bottom of Enclosed Space Floor	L_F	15	cm	California DTSC/HERO default (California DTSC 2014)
Building Ventilation Rate*	Q_b	3.4E+04	cm^3/s	Calculated: $A_{b,sg} \times AXR_b \times H$
Area of Enclosed Space Below Grade†	$A_{b,sg}$	1.0E+06	cm^2	California DTSC/HERO default (California DTSC 2014)
Building Air Exchange Rate†	AXR_b	0.5	hr^{-1}	California DTSC/HERO default (California DTSC 2014)
Building Height†	H	244	cm	California DTSC/HERO default (California DTSC 2014)
Vapor Flow Rate into Building	Q_{soil}	5	L/min	California DTSC/HERO default (California DTSC 2014)
Soil Properties				
Average Soil Temperature	T_s	16.7	°C	Site-specific; lower end of average temperature for general region where site is located; from Figure 8 in USEPA (2017a)
Dry Bulk Density	ρ_b	1.6	g/cm^3	USEPA (2017a) default soil properties for loamy sand
Total Porosity	η	0.39	cm^3/cm^3	USEPA (2017a) default soil properties for loamy sand
Water-Filled Porosity	θ_w	0.076	cm^3/cm^3	USEPA (2017a) default soil properties for loamy sand

Notes: California DTSC = California Environmental Protection Agency, Department of Toxic Substances Control; HERO = California Environmental Protection Agency, Human and Ecological Risk Office; USEPA = U.S. Environmental Protection Agency.
* Building ventilation rate (Q_b) and vapor flow rate into building (Q_{soil}) were separate model input variables in older versions of USEPA J&E Model. The latest USEPA spreadsheet (2017b) uses the ratio Q_{soil}/Q_b as a single input variable in the default mode.
† These building parameters are used to calculate building ventilation rate (Q_b) as model input.

The air residential screening level, J&E modeled AFs by sample depth, and corresponding preliminary remediation goals for PCE in soil vapor are summarized in Table I-7.

Table I-7. Depth-specific attenuation factor and remediation goals for PCE.

Sample Depth (feet bgs)	Residential Air Screening Level (ug/m^3)	Depth-Specific Attenuation Factor	Preliminary Remediation Goal (ug/m^3)
5–12 (Shallow Zone)	0.46	0.001*	460
20	0.46	0.0003	1,500
25	0.46	0.00025	1,800
30	0.46	0.00022	2,100

Note: *Default attenuation factor value in the state vapor intrusion guidance.

The J&E model-derived AF for potential attenuation from the intermediate zone (20–30 feet bgs) to the shallow zone (5 to 12 feet bgs), after accounting for the default AF of 0.001 for the shallow zone, is an additional factor of 0.22 to 0.3. These model-derived AFs were used to develop the depth-specific preliminary remediation goals for PCE in intermediate zone soil vapor.

I.4.2.3 Comparison with Measured Data

The model-derived AFs were compared with the ratios (empirical AFs) of measured soil vapor data in the shallow and intermediate zones to further support the use of the model-derived AFs for developing the depth-specific preliminary remediation goals for PCE in intermediate zone soil vapor. Table I-8 presents the summary statistics for the calculated ratios of sample pairs at the depths between the intermediate (20–30 feet bgs) and the shallow zone (5 feet bgs).

Table I-8. Summary statistics on ratios of measured PCE concentrations between intermediate (20–30 feet bgs) and shallow (5 feet bgs) zones.

Ratio by Sample Depth (ft bgs)	5 Feet over 20–25 Feet	5 Feet over 26–30 Feet
Number of Sample Pairs	20	32
Minimum Ratio	0.0079	0.0073
Mean Ratio	0.33	0.26
Median Ratio	0.28	0.24
Maximum Ratio	0.95	0.79

The J&E model-derived AFs for potential attenuation from the intermediate zone to the shallow zone (0.22 to 0.3) agree with the mean and median ratios values in Table I-8.

I.4.2.4 Summary and Lessons Learned

1. Site-specific AFs using the J&E model were calculated for different sample depths to support development of the preliminary remediation goals to guide the operation and shutdown of the SVE system.
2. The model-derived AFs from the intermediate zone to the shallow zone (0.22 to 0.3) are similar to the mean and median ratios (0.24 to 0.33) based on measured soil vapor data. The ranges of the empirical ratios span approximately two orders of magnitude, indicating possible spatial and/or temporal variability of the measured data set.
3. A post-remedy health-risk assessment was also conducted following the cleanup to verify that cumulative VI cancer risks based on shallow- and intermediate-zone soil vapor data are below or at

the lower end of the risk management range of 1×10^{-6} to 1×10^{-4} for the commercial and residential land use scenarios.

4. The uncertainties associated with the modeling and data variability (to be considered as a line of evidence) were addressed by performing indoor air sampling in the newly constructed buildings before occupancy by residents.

5. A VI mitigation system (VIMS) has also been installed at the proposed residential buildings due to regional groundwater impacts. The operations, maintenance, and monitoring plan was prepared for the VIMS and includes monitoring of exterior soil vapor probes, sub-slab vapor probes, and indoor air (if sub-slab vapor concentrations exceed the action levels).

I.4.3 Modeling Used for Targeting Outreach and Indoor Air Sampling

This case study illustrates the use of VI modeling, community outreach, and VI mitigation at a site in Las Vegas, Nevada. Following soil vapor sampling, the J&E model was used to estimate indoor air PCE concentrations at residences above the groundwater plume. Residents were selected for information outreach and voluntary indoor air sampling based on the model results and plume maps. For homes with PCE concentrations exceeding the Nevada health screening level, residents were offered sub-slab depressurization (SSD) systems at no cost to the homeowners.

I.4.3.1 Purpose and Objectives

Upon discovery of a groundwater plume of dissolved-phase PCE beneath a residential area, the regulatory agency developed the following objectives:

1. Use VI modeling to select residences for targeted outreach, indoor air sampling, and mitigation, if warranted.

2. Verify model predictions using indoor air concentrations, once obtained.

3. Use multiple lines of evidence to set cleanup goals for the plume.

I.4.3.2 Early Case Evolution

The site, known as Maryland Square for the shopping center in which the source area was located, is in central unincorporated Clark County, Nevada, several miles east of the Las Vegas Strip resort and entertainment district. Although the area is unincorporated, properties have Las Vegas addresses. The source area is a former dry cleaner that operated from approximately 1969–2000. A spill of approximately 100 gallons of PCE was documented in 1982. Additionally, it is believed that multiple smaller releases occurred due to poor housekeeping practices and improper disposal of spent PCE.

The discovery of PCE in groundwater near the source area was reported to the Nevada Division of Environmental Protection (NDEP) in 2000. By 2006, it was documented that a plume of dissolved PCE in groundwater extended downgradient from the source, beneath a shopping mall, and beneath a residential area. Currently the plume extends more than 1 mile downgradient from the source. In 2007, NDEP directed the responsible party (RP) to advance soil borings and collect soil vapor samples in the residential area.

Soil vapor samples were collected from borings at 5-foot intervals, starting at 5 feet bgs and extending to just above the groundwater table, which was present at depths of approximately 15–20 feet bgs. After removing samples with detections of the leak detection tracer gas, PCE concentrations ranged from 400 to 170,000 micrograms per cubic meter ($\mu g/m^3$) in 27 soil vapor samples. As expected, soil vapor

concentrations were generally higher for the deeper samples, closer to the water table. Figure I-1 shows the concentrations of PCE in soil vapor vs. sample depth.

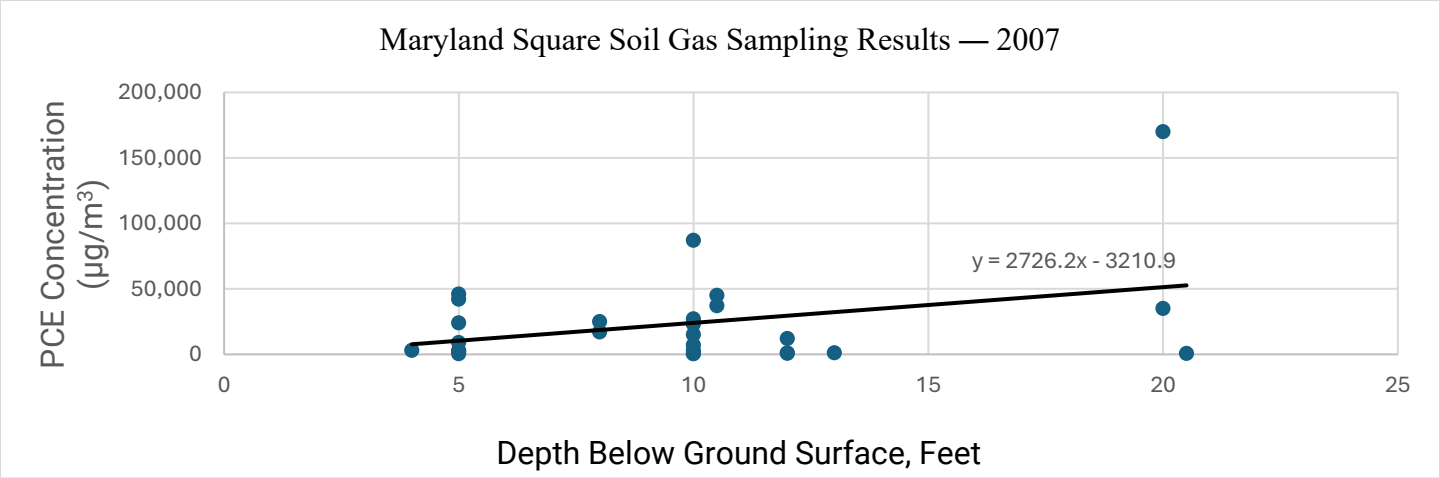


Figure I-1: PCE soil vapor concentrations as a function of sample depth.

I.4.3.3 Modeling

In 2007, following receipt of the soil vapor sampling results, NDEP used the J&E model to predict indoor air PCE concentrations in homes above the plume. Model results were compared to the Nevada health screening level of 32 µg/m^3 for PCE in residential indoor air at the time. This concentration was developed from USEPA guidance and a survey of other states and was based on chronic health impacts (cancer risk).

For inputs, model defaults were used for most parameters. NDEP used slab on-grade foundation, a temperature of 25°C, and sandy soil. The PCE concentration and sampling depth was used for each of the samples, and the model was run to calculate indoor concentrations of PCE. Table I-9 shows the model-predicted indoor air PCE concentrations based on depth and soil vapor concentration.

Table I-9: J&E model-predicted indoor air PCE concentrations as a function of depth below grade to soil vapor sample, and soil vapor PCE concentrations.

Sample ID	Depth (feet bgs)	Soil Vapor PCE (µg/m^3)	J&E Modeling Predicted Indoor Air PCE (µg/m^3)
SVB-01-05	5	2,500	6.1
SVB-02-04	4	3,000	8.1
SVB-03-05	5	46,000	112.1
SVB-03-12	12	800	1.1
SVB-04-05	5	400	1.0
SVB-04-12	12	1,000	1.4
SVB-05-08	8	25,000	46.8
SVB-05-13	13	1,100	1.6
SVB-05-98	8	17,000	31.8
SVB-06-12	12	12,000	17.1
SVB-08-05	5	2,700	6.6
SVB-08-10	10	7,100	11.5
SVB-08-910	10	15,000	24.3

Sample ID	Depth (feet bgs)	Soil Vapor PCE (µg/m³)	J&E Modeling Predicted Indoor Air PCE (µg/m³)
SVB-09-05	5	9,000	21.9
SVB-09-10	10	23,000	37.2
SVB-10-05	5	42,000	102.4
SVB-10-10	10	27,000	43.7
SVB-11-10	10	500	0.8
SVB-11-910	10	400	0.6
SVB-12-10	10	3,000	4.9
SVB-13-05	5	24,000	58.5
SVB-13-10.5	10.5	37,000	59.9
SVB-13-20	20	35,000	36.9
SVB-13-910.5	10.5	45,000	72.8
SVB-14-10	10	87,000	140.8
SVB-14-20	20	170,000	179.1
SVB-16-20.5	20.5	600	0.6

Note: Yellow highlighting indicates that the predicted concentration exceeds the NDEP health screening level of 32 µg/m³.

NDEP did not run the J&E model using groundwater concentrations as inputs; however, NDEP compared model-predicted results to approximate groundwater concentrations near the soil vapor sampling points. Figure I-2 shows the predicted indoor air PCE concentrations as a function of groundwater PCE concentrations. The chart indicates that the first cluster of predicted indoor air concentrations exceeding 32 µg/m³ occurs at groundwater concentrations between 350 and 400 µg/L, consistent with separate NDEP screening tables developed by running the J&E model using PCE groundwater concentrations. Using the averaging line, PCE concentration in indoor air would be predicted to exceed 32 µg/m³ at groundwater concentrations above 700 µg/L.

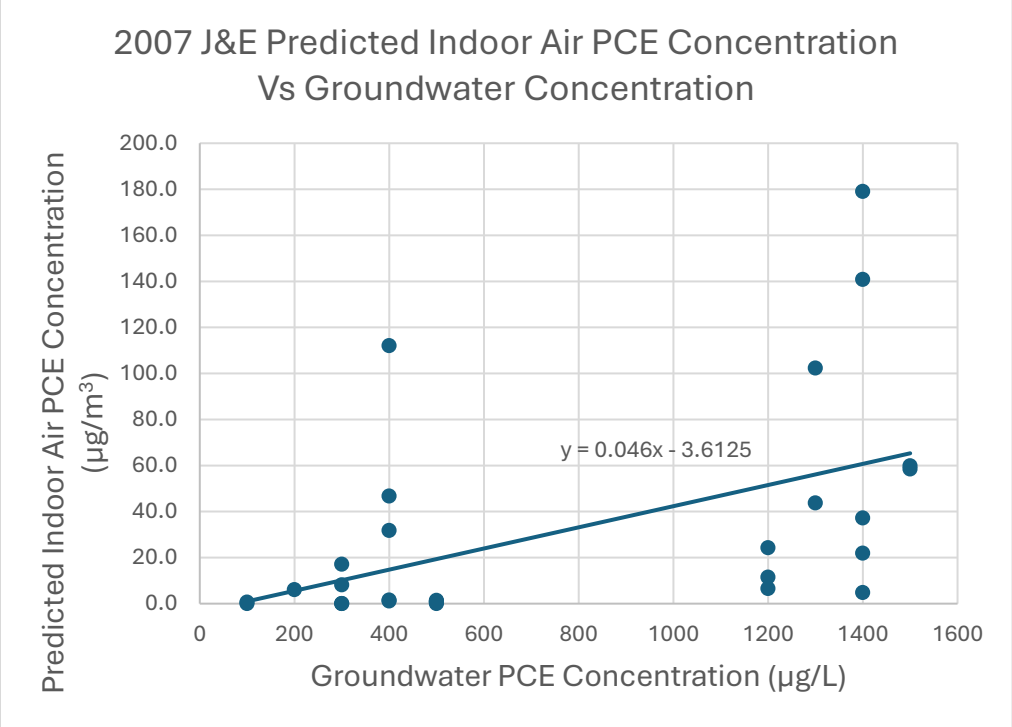


Figure I-2: Model-predicted indoor air concentrations, calculated from soil vapor concentrations, relative to PCE groundwater concentrations near the sampling locations.

I.4.3.4 Indoor Air Sampling and Regulatory Requirements

In 2007, to be conservative in protecting human health, NDEP required the RP to offer indoor air sampling, at no cost to the homeowner to every household located above the plume where groundwater concentrations exceeded 100 µg/L. From 2007–2008, air samples were collected from 98 single-family homes. PCE was detected in 41 homes and exceeded the 32 µg/m^3 screening level in 15 homes. The highest PCE concentration measured was 110 µg/m^3. NDEP required the RP to offer vapor mitigation, in the form of SSD systems, to residents with indoor air PCE concentrations exceeding 32 µg/m^3. From 2007 to 2017, a total of 18 SSD systems were installed at individual homes. As of 2024, all of these systems remain operational.

All of the homes with PCE concentrations exceeding the 32 µg/m^3 screening level were located above groundwater concentrations exceeding 500 µg/L. Due to the distance between the impacted homes and the source area (> 0.5 miles) it is assumed that vapors emanating from the groundwater are the only source of PCE impacting the indoor air. The primary transport pathway appears to be through the vadose zone and slab-on-grade foundations, although preferential pathways through coarser material, such as utility trench fill, may also be affecting contaminant transport.

I.4.3.5 Comparison with Measured Data

Using the J&E model most recently updated in 2018, NDEP calculated predicted indoor air PCE concentrations based on groundwater concentrations rather than soil vapor concentrations. **Figure I-3** shows actual measured indoor air concentrations versus groundwater concentrations compared to predicted concentrations using sand or sandy loam as the soil type in the J&E model.

For the 2024 indoor air modeling based on groundwater concentrations, NDEP initially used the same conditions as the 2007 modeling, substituting groundwater concentrations for soil vapor concentrations as the source medium. A value of 18 feet (5.5 meters) bgs was selected for the Depth Below Grade to Water Table parameter, consistent with the average depth to water beneath the impacted homes. Using sand for the soil type resulted in predicted indoor air PCE concentrations that were substantially higher than measured concentrations. Changing the soil type to sandy loam resulted in concentrations that were much closer to the measured concentrations. For the sandy loam soil, the model closely matched results for groundwater concentrations in the 1,200–1,300 µg/L range. The model underpredicted indoor air concentrations at higher groundwater concentrations. This may be due to the fact that the model output is linear when changing only the depth to the water table, but the measured results appear to better fit a second order or power curve.

In 2015, NDEP issued the record of decision (ROD) for the case. Multiple remedial techniques, including soil excavation and in situ oxidation in the area of the former dry cleaner and groundwater pump-and-treat downgradient from the initial source area, were selected. The intent of the pump-and-treat system is to reduce the mass flux of dissolved-phase PCE in groundwater toward the residential area. The groundwater cleanup goal for PCE is concentrations <100 µg/L. PCE concentrations exceeding 32 µg/m^3 in indoor air have not been documented for homes above groundwater with PCE concentrations <100 µg/L. Downgradient from the pump-and-treat hydraulic containment, the distal plume is monitored quarterly for evidence of natural attenuation.

The ROD requires continued operation and maintenance of the SSD units installed at residences until they are no longer required for reducing PCE concentration to <32 µg/m^3 in indoor air. The RP must also offer to provide annual indoor air sampling to all residents with homes above groundwater plume concentrations exceeding 100 µg/L.

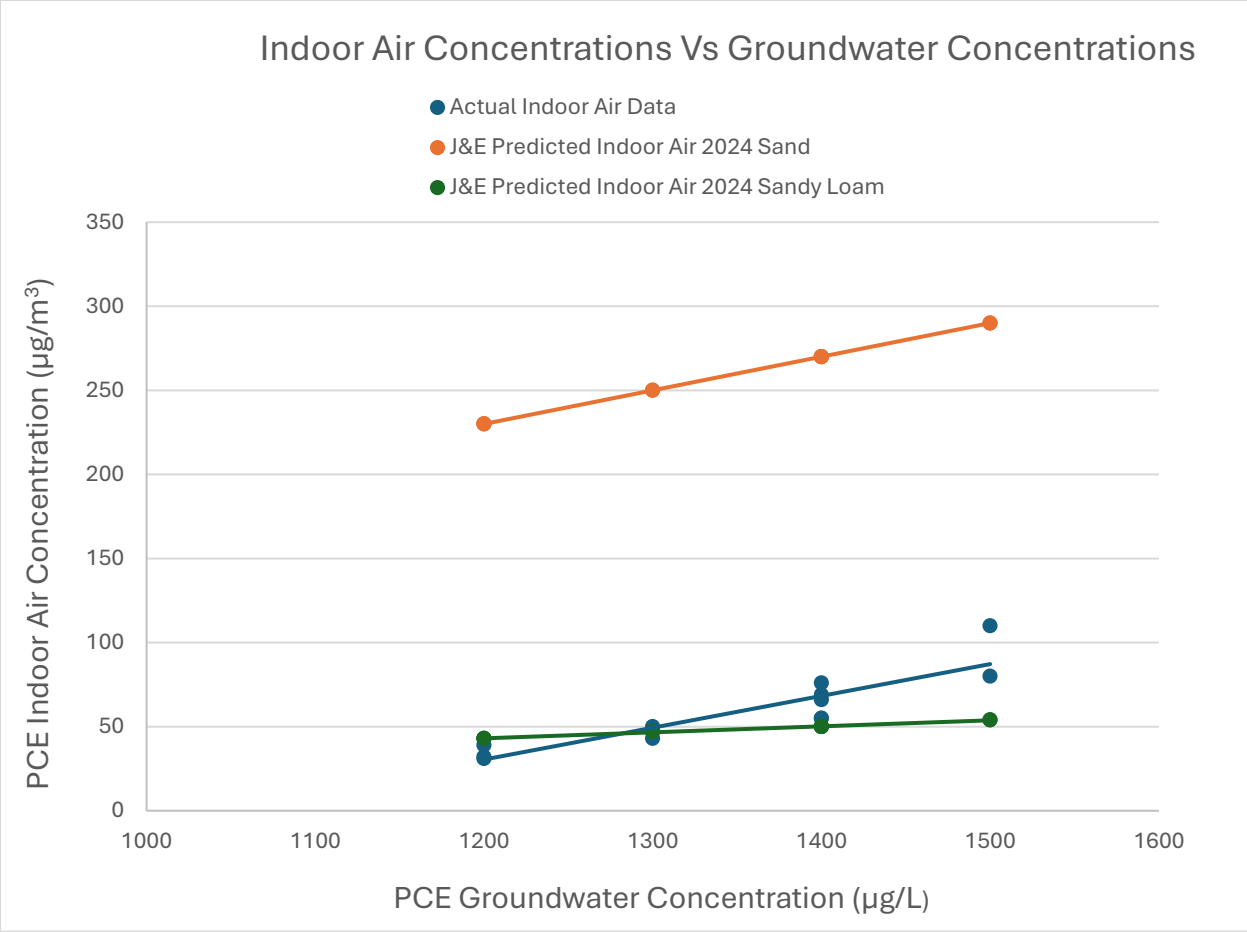


Figure I-3: Actual indoor air PCE concentrations and predicted concentrations versus PCE groundwater concentrations.

I.4.3.6 Summary and Lessons Learned

This case study illustrates the use of VI modeling in the decision-making process. The J&E model was used to conservatively predict indoor air concentrations in homes above a groundwater PCE plume. Model results were used to select households for community outreach, indoor air sampling, and ultimately VIMS in homes with PCE air concentrations exceeding health standards.

Lessons Learned

1. The J&E model can be used to reasonably predict indoor air concentrations of PCE based on exterior soil vapor or groundwater PCE concentrations.
2. Running the model using conservative input parameters is protective of human health.
3. The J&E model is highly sensitive to soil type. When soil type is unknown at a site, the use of sand is conservative and will result in the highest predicted PCE concentrations. Site-specific physical soil data should be collected, and model inputs varied accordingly, to more accurately predict indoor air concentrations.

APPENDIX J: VAPOR INTRUSION MITIGATION SYSTEM CONSTRUCTION QUALITY ASSURANCE PLAN OUTLINE

This appendix is designed to provide an example template for preparation of a construction quality assurance (CQA) plan. While specific components can vary depending on the site and regulatory requirements, a comprehensive plan may include the following:

1. **Introduction:** This section will provide a general introduction to the project purpose and may include the following:
    a. Purpose and scope
    b. Key terms
    c. Reference documents
2. **Scope of Construction:** This section will detail the overall scope of the vapor intrusion mitigation system (VIMS) and may include the following information:
    a. Design
    b. System materials
    c. Subcontractors and suppliers
    d. General and project quality specifications and contingencies
    e. Schedule
    f. Initial and future operation, maintenance, and monitoring actions
3. **Project Responsibilities:** This section will detail the responsibilities of the various VIMS-related project team members:
    a. Project manager
    b. Engineer(s)
    c. Safety
    d. Field inspector
    e. System installer
    f. Related trades
    g. Other
4. **Construction Installation Observation:** This section will detail the planned installation observation/oversight and may include the following information:
    a. Field notes
    b. Photographs
    c. Action Items (conditions observed during the construction process that did not conform to the project specifications and require a remedy)
    d. Quality assurance/quality control (QA/QC)
        i. General oversight

ii. Testing (as recommended by system component manufacturers)

5. **Project Communication:** This section will detail the recommended project communication expectations and may include templated forms to maintain a consistent communication approach. It may include the following information:
   a. Expected frequency of meetings with the construction team (e.g., daily, weekly, as needed)
   b. Plan for meetings to discuss work deficiencies/issues
   c. A public communication plan
6. **Technical Records Handling:** This section will include technical records for contractors and oversight and may include project templates for anticipated documentation. It may include the following information:
   a. Contractor records
   b. Oversight and QA/QC reports
7. **Control of Nonconformances:** This section details how nonconforming issues will be handled with the project team, with the goal of implementing corrective actions if and when nonconformance issues arise.
8. **Conclusions:** This section may summarize the overall intent and basis for the CQA plan and the expectations and requirements for the various VIMS team members during construction.

This portion of the page left blank intentionally. The next appendix begins on the following page.

APPENDIX K: VAPOR INTRUSION MITIGATION STEWARDSHIP PLAN OUTLINE

Institutional controls (ICs) are a form of land use controls that provide protection from exposure to contaminants on a site. While ICs consist of administrative or legal restrictions on a site, they can also use engineering controls (ECs) such as a vapor intrusion mitigation system (VIMS). A vapor intrusion mitigation stewardship plan outlines the strategies and procedures for the long-term management and maintenance of a VIMS at a site. These plans are crucial for ensuring the continued effectiveness of the VIMS in protecting human health and the environment. This plan details how a VIMS will be managed, monitored, and enforced over the long term to ensure it remains effective and protective. The plan clearly defines the responsibilities of various parties, ensuring that there is accountability for the long-term management of the ICs.

For effectively managing contaminated sites, a comprehensive approach integrates a stewardship plan; an operation, maintenance, and monitoring (OM&M) Plan; and ICs. The OM&M plan concentrates on the practical aspects of the installed VIMS, detailing its operation, regular maintenance, and ongoing monitoring. The stewardship plan, however, takes a wider view, providing a long-term management strategy that extends beyond the remediation phase to address residual contamination and the long-term performance of ECs and ICs.

While specific components can vary depending on the site and regulatory requirements, a comprehensive plan may include the following:

1. **Description of Engineering Controls:**
    a. Detail the activity or requirements of the VIMS.
    b. Reference the legal documents (e.g., deed restrictions, ICs, ordinances) that establish the VIMS.
    c. Provide photos and specifications of typical system components.
    d. Provide information relating to the mitigation system alarm/monitors.
2. **Roles and Responsibilities:**
    a. Identify all personnel responsible for implementing, monitoring, maintaining, and enforcing the ECs (e.g., property owner, property manager, tenants, regulatory agencies, local government).
    b. Clearly define the specific duties and obligations of each party.
    c. Detail procedures to notify new occupants and update all occupants for planned activities.
    d. Provide instructions for whom to contact in the event of an alarm condition or unusual noise related to the mitigation system.
3. **Monitoring and Performance Evaluation:**
    a. Establish a schedule and protocol for routine monitoring of the building and/or VIMS.
    b. Explain restrictions to access, perform construction on, or use portions of the property.
    c. Determine the parameters to be monitored (e.g., VIMS performance, indoor air quality, condition/integrity of VIMS components).
    d. Outline the methods for collecting and evaluating monitoring data.
    e. Define performance criteria to assess whether the VIMS is achieving the design objectives.

4. **Enforcement Mechanisms:**
    a. Specify who has the authority to enforce the VIMS.
    b. Describe the procedures for addressing violations or breaches of the ECs.
    c. Identify the legal and administrative actions that can be taken to ensure compliance.
    d. Determine whether legal and administrative agreements are needed between private parties, such as access agreements and monetary obligations.
5. **Long-Term Management and Maintenance:**
    a. Detail the activities required to maintain the effectiveness of the system over time (e.g., record-keeping, inspections, public awareness).
    b. Address the maintenance of any ECs that the system may rely on.
    c. Verify the overall condition of all ECs in place.
6. **Information and Data Management:**
    a. Establish a system for managing and storing all relevant information related to the VIMS, including discussions, field reports, monitoring data, and inspection reports.
    b. Retain records for the lifespan of the building or as dictated by insurance or legal requirements.
    c. Specify how this information will be accessed and shared with relevant stakeholders.
7. **Contingency Planning and Corrective Actions:**
    a. Develop procedures for responding to situations where the VIMS is not functioning as intended (system not operational as designed) or where unexpected indoor air quality issues are discovered.
    b. Outline the steps for implementing corrective actions to restore the effectiveness of the VIMS.
8. **Modification or Termination Procedures:**
    a. Describe the process for modifying or terminating the ECs if site conditions change or if the VIMS is no longer warranted.
    b. Develop a transition plan in the event of property ownership transfers or new occupancy, including access agreements or operational requirements.
    c. Specify the regulatory approvals required for any modifications or terminations.
9. **Public Involvement and Communication:**
    a. Outline how the site occupants or community will be informed about the VIMS and the stewardship plan.
    b. Review ICs or legal requirements to identify information not intended for public disclosure, such as specifics of the building's systems, security measures, and operational details that, if exposed, could compromise safety or security.
    c. Describe opportunities for public input and engagement in the long-term management of the site.

APPENDIX L: VAPOR INTRUSION MITIGATION EXAMPLE CURTAILMENT PLAN OUTLINE

This example document details the elements of a plan for safely and effectively reducing or decommissioning vapor intrusion mitigation system (VIMS) operation when monitoring shows the VIMS is no longer required for occupant protection against vapor intrusion (VI). Refer to the Vapor Intrusion Mitigation System Curtailment and Shutdown Fact Sheet for more details and considerations. Specific components can vary depending on the site and regulatory requirements, but a comprehensive plan may include the following elements:

1. **Introduction:** This section provides a description and rationale for the VIMS and curtailment plan.
    a. **Purpose and Scope:** To establish a protocol for the reduction or termination of VIMS operation while ensuring the continued protection of human health and the environment.
    b. **Site Background:** Briefly describe the site conditions, including the history of contamination, contaminants of concern, and the VIMS installed.
    c. **VIMS Description:** Describe the installed VIMS, including its design, components, how it operates, and overall history of operation.

2. **Objectives:** This section specifies the intent of the document
    a. Define the conditions under which reduction or termination of the VIMS operation can be considered.
    b. Discuss ways to ensure that the shutdown process does not pose a risk to human health or the environment.
    c. Establish a monitoring program to verify that risk associated with VI remains acceptable after system shutdown.
    d. Consider regulatory approval requirements for the curtailment process.

3. **Regulatory Framework:**
    a. Identify the applicable federal, state, and local regulations and guidance documents that govern VI mitigation and system curtailment.
    b. Outline the steps for regulatory review submittals and timelines for review and acceptance.

4. **Prerequisites for Curtailment** (see the Vapor Intrusion Mitigation System Curtailment and Shutdown Fact Sheet):

    The following conditions must be demonstrated before VIMS curtailment can be considered:

    a. **Source Control:** The source of subsurface contamination has been adequately addressed through remediation or natural attenuation.
    b. **Subsurface Vapor Reduction:** Substantial and sustained reduction or control of subsurface vapor concentrations of contaminants of concern has been adequately addressed.
    c. **Indoor Air Quality Standards:** Demonstrate consistent attainment of acceptable indoor air quality standards for vapor-forming chemicals that may be present as a result of VI.
    d. **VIMS Performance Evaluation:** A comprehensive evaluation of the VIMS performance data, demonstrating its effectiveness in mitigating VI.

e. **Conceptual Site Model (CSM) Reevaluation:** The CSM has been updated to reflect current site conditions and demonstrates a low risk of future VI (see **Chapter 4: Conceptual Site Model**).

f. **Preferential Pathway Evaluation:** All potential preferential pathways for VI (e.g., cracks, utility conduits) have been identified and properly sealed or mitigated such that preferential pathways are no longer a source of VI (see the **Vapor Intrusion Preferential Pathways Fact Sheet** and the **Preferential Pathway Sealing and Ad Hoc Ventilation Technology Information Sheet**).

5. Curtailment Strategy:

The curtailment strategy involves a three-phased approach with specific actions and monitoring requirements for each phase:

- **Phase 1: System Optimization and Reduced Operation:**
  a. Optimize VIMS operation to minimize energy consumption and operational costs.
  b. Reduce operating time (e.g., from continuous to intermittent operation).
  c. Increase monitoring frequency to assess the effects of reduced operation.
- **Phase 2: Temporary Shutdown:**
  a. Temporarily shut down the active components of the VIMS (e.g., blowers) for a specified period.
  b. Continue intensive monitoring of subsurface vapor and indoor air.
  c. Evaluate monitoring data to assess the potential for rebound in contaminant concentrations.
- **Phase 3: System Termination/Decommissioning:**
  a. If monitoring data from Phase 2 demonstrates that VI is not occurring, VIMS operation may be terminated, pending approval from all interested parties.
  b. Develop a plan for decommissioning the VIMS components, if necessary, in accordance with applicable regulations.
  c. Implement a long-term monitoring plan.

6. Monitoring Plan:

A detailed monitoring plan is essential to gauge the impact of VIMS shutdown. The post-shutdown monitoring plan should include the following elements, as applicable:

a. **Monitoring Objectives:** Clearly defined objectives, such as verifying the continued absence of VI.

b. **Monitoring Locations:** Locations for subsurface vapor and indoor air sampling, including background locations.

c. **Multiple Lines of Evidence:** Where applicable, establish additional criteria to demonstrate the effectiveness of any remaining passive VIMSs (e.g., passive barriers, passive sub-slab ventilation systems), such as documenting a cross-slab pressure differential operating as a passive system (see the **Multiple Lines of Evidence Fact Sheet**).

d. **Sampling Frequency and Duration:** The frequency and duration of monitoring for each phase of the curtailment process.

e. **Analytical Parameters:** The specific contaminants of concern to be analyzed.

f. **Sampling and Analytical Procedures:** Standardized procedures for sample collection, handling, and analysis.

g. **Data Evaluation and Reporting:** Procedures for evaluating monitoring data and reporting results to regulatory agencies and stakeholders.

h. **Action Levels:** Predetermined action levels for contaminant concentrations that would trigger specific responses, such as VIMS reactivation.

7. **Contingency Plan:**

   A contingency plan outlines the actions to be taken if monitoring results indicate a rebound in VI or exceedance of action levels. The plan should include the following:

   a. **VIMS Reactivation:** Procedures for quickly and efficiently reactivating the VIMS.

   b. **Increased Monitoring:** Increased frequency or scope of monitoring, as appropriate and in accordance with applicable regulatory requirements.

   c. **Additional Investigation:** Further investigation to identify the cause of the rebound, as necessary.

   d. **Alternative Mitigation Measures:** Implementation of alternative mitigation measures, if necessary.

8. **Community Involvement and Communication (see also Chapter 3: Community Engagement)**

   Establish a plan for communicating with stakeholders and providing regular updates on the progress of the curtailment process and monitoring results. The plan should include the following parties:

   a. Property owners and occupants

   b. Local community members

   c. Applicable regulatory agencies

9. **Reporting and Documentation:**

   Maintain thorough documentation of all activities related to VIMS curtailment, including the following:

   a. System operation and maintenance records

   b. Monitoring data and reports

   c. Regulatory correspondence

   d. Deviations from the approved plan

   e. Prepare and submit reports to regulatory agencies as required.

10. **Project Schedule:**

    a. Provide a timeline for the implementation of the curtailment plan, including key milestones and decision criteria.

    b. Identify milestones that need to be met that could otherwise interrupt the approval process.

11. **Approval:**

    a. This curtailment plan must be reviewed and approved by the relevant regulatory agency (if applicable) prior to implementation.

By adhering to a detailed, preapproved curtailment plan, the objectives are clear, and the site can safely and effectively transition from an active VIMS to a passive VIMS to VIMS shutdown or alternative long-term monitoring strategy that protects human health and the environment.